Handbook for CRPL Ionospheric Predictions Based on Numerical Methods of Mapping

Handbook 90

United States Department of Commerce
National Bureau of Standards

CENTRAL RADIO PROPAGATION LABORATORY

The Central Radio Propagation Laboratory at Boulder, Colorado, is the central agency of the Federal Government for the collection, analysis, and dissemination of information on propagation of radio waves at all frequencies along the surface of the earth, in the atmosphere, and in space, and performs scientific studies looking toward new techniques for the efficient use and conservation of the radiospectrum. To carry out this responsibility, the CRPL—

1. Acts as the central agency for the conduct of basic research on the nature of radio waves, the pertinent properties of the media through which radio waves are transmitted, the interaction of radio waves with those media, and on the nature of radio noise and interference effects. This includes compilation of reports by other foreign and domestic agencies conducting research in this field and furnishing advice to Government and non-Government groups conducting propagation research.
2. Performs studies of specific radio propagation mechanisms and performs scientific studies looking toward the development of techniques for efficient use and conservation of the radiofrequency spectrum as part of its regular program or as requested by other Government agencies. In an advisory capacity, coordinates studies in this area undertaken by other Government agencies.
3. Furnishes advisory and consultative service on radio wave propagation, on radiofrequency utilization, and on radio systems problems to other organizations within the United States, public and private.
4. Prepares and issues predictions of radio wave propagation and noise conditions and warnings of disturbances in these conditions.
5. Acts as a central repository for data, reports, and information in the field of radio wave propagation.
6. Performs scientific liaison and exchanges data and information with other countries to advance knowledge of radio wave propagation and interference phenomena and spectrum conservation techniques, including that liaison required by international responsibilities and agreements.

CRPL IONOSPHERIC PREDICTIONS

The CRPL Ionospheric Predictions are issued monthly as an aid in determining the best sky-wave frequencies over any transmission path, at any time of day, for average conditions for the month. Issued three months in advance, each issue provides tables of numerical coefficients that define the functions describing the predicted world-wide distribution of foF2 and F2-M3000, and maps for each even hour of Universal Time of F2-Zero-MUF and F2-4000-MUF.

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. Price 15 cents (single copy). Subscription price: $1.50 a year, 50 cents additional for foreign mailing.

(Descriptive material and purchase information on punched card decks of predicted coefficients may be obtained from the Prediction Services Section, CRPL, National Bureau of Standards, Boulder, Colorado.)

UNITED STATES DEPARTMENT OF COMMERCE • Luther H. Hodges, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

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S. M. Ostrow

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Preface

This Handbook describes how to use CRPL Ionospheric Predictions Based on Numerical Methods of Mapping, (formerly CRPL-D series) first appearing in the January 1963 issue. Previous predictions were prepared by manual methods and designed primarily for graphical solution of high frequency propagation problems. The current version is prepared by numerical mapping methods using an electronic computer, and the predictions are presented in two forms, giving the user the choice of either computer or graphical methods. Those having access to a modern electronic computer derive maximum benefits from the prediction system described here. However, even when a computer cannot be used, the current prediction maps provide more information than the earlier zone prediction charts.

Requirements for high frequency radio communication services are constantly increasing. Although other communication systems, such as satellites, can be expected to carry a larger proportion of the world's communications, efficient utilization of the high frequency spectrum will continue to be necessary for the foreseeable future. The CRPL ionospheric predictions provide useful tools for effective frequency allocation, for efficient use of assigned frequencies, and for developing specifications for engineering design of high frequency communications equipment and circuits.

The predictions described here are prepared by the Central Radio Propagation Laboratory of the National Bureau of Standards as part of its continuing responsibility for improvement of radio communications by research on the propagation of radio waves. The methods and applications of ionospheric mapping and predictions by means of numerical analysis and high speed computers were developed by R. M. Gallet and W. B. Jones. These methods are applicable to a wide variety of problems where mapping of physical variations is required. Miss M. PoKempner participated in the large scale application of the numerical mapping method to ionospheric characteristics and was responsible for the organization of the procedures used in the new series of ionospheric predictions. G. W. Haydon and D. L. Lucas have been responsible for making use of the new methods directly in a number of computer applications to high frequency communication problems. Many other staff members contributed to this work in various ways.

A. V. Astin, Director

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Central Radio Propagation Laboratory Ionospheric Predictions Based on Numerical Methods of Mapping (formerly CRPL-D series), is described. The Gallet-Jones method of numerical mapping, which is the basis of these predictions, is briefly described. Use of an electronic computer for applying the predictions is recommended. Graphical F2-layer prediction maps, derived from the numerical predictions, are described in detail. Instructions and auxiliary material are provided for applying the graphical map predictions by manual methods. Some limitations of the predictions and aspects of ionospheric radio propagation are discussed briefly.

1. INTRODUCTION

This handbook is for use with the Central Radio Propagation Laboratory Ionospheric Predictions successor to CRPL Series D. It provides instructions and supplementary material for use with the predictions and replaces National Bureau of Standards Circular 465, "Instructions for the Use of the Basic Radio Propagation Predictions," issued August 27, 1947. NBS Circular 465 described methods for using graphical predictions developed during World War II. The new predictions prepared by numerical analysis methods using an electronic computer have an entirely different approach providing more information in a form readily adaptable to the specific requirements of each user. The first number of the new CRPL predictions is the January 1963 issue. CRPL-D220, issued December 1962, is the last of the old CRPL Series D.

The basic form of the F2-layer predictions in the new series is a table of numerical coefficients defining a function which represents the world-wide and diurnal variations of an ionospheric characteristic. This function, referred to as the "numerical map" of the characteristic, has the form of a finite series of simple terms consisting of elementary functions of latitude, longitude and time, each multiplied by the appropriate coefficient given in the table. Employing these numerical maps, an electronic computer may be used for all computations for a particular problem, the computer performing all the necessary calculations. Additional factors in propagation may be added to the computer program as required. The computer, therefore, makes possible the most efficient and effective application of these predictions. Computer methods are particularly useful for more complicated propagation problems and for quantity production of detailed predictions for large numbers of circuits. Given the numerical maps, a medium or small size electronic computer is adequate for many propagation problems.

In the new predictions, graphical maps are derived from the predicted numerical maps. They are provided for use when a computer is not available or practical. While similar in appearance to the four zone time charts formerly appearing in the CRPL-D series, they are quite different in type. They have been designed for use with the same type of graphical operations as were used with the older form of prediction charts. Two of the new prediction maps appear on a page in order to keep each issue to a reasonable size while presenting as complete a set of graphical maps as possible. Although greater precision is obtained with a computer, the precision afforded by the graphical maps is in accordance with the accuracy of the prediction process.

A new feature is the polar gnomonic presentation of the predictions for 0000 and 1200 GMT (orUT). Space does not permit inclusion of a complete set of polar maps in the monthly predictions. However, polar maps for other hours can be obtained by special arrangement. The outlines of the land masses on the polar maps and the modified cylindrical projection world map are approximate and intended only as a guide. The latitude and longitude scales, rather than the land mass outlines, should be used for locating positions on the earth's surface.

Definitions and usage of "MUF" (maximum usable frequency) in this handbook follow the recommendations of the International Radio Consultative Committee (C.C.I.R.) [I.T.U., 1959]. Other symbols and terminology follow the recommendations of the World-Wide Soundings Committee, U.R.S.I. [Piggott and Rawer, 1961].

Maps of observed ionospheric data for selected time periods will be prepared in the same numerical and graphical forms as the predictions, and may be obtained by special arrangement.

Comments or suggestions on the new series of predictions and on these instructions are most welcome, particularly reports on experience in use of the predictions.

2. NUMERICAL MAPS AND THEIR APPLICATION

The predictions in the new form of the Bureau's CRPL Ionospheric Predictions are based on the numerical methods of mapping developed by R. M. Gallet and W. B. Jones [Jones and Gallet, 1962a, 1962b]. The tables of coefficients defining numerical maps of foF2 and F2-M3000, Tables 1 and 2, provide the basic input data from which, with appropriate auxiliary information, predictions for any application may be derived by use of a computer. Since the specific requirements of different organizations and individuals are quite varied, and since there are many different computer systems in use, it is impractical to present detailed programming instructions for use of the tables of numerical map coefficients in this handbook. In this section, the nature and meaning of the numerical map coefficients will be indicated. The papers [Jones and Gallet, 1962a, 1962b] should be consulted before attempting to prepare a computer program for use of the coefficients.

In addition to the F2-layer numerical maps described in this section, information on regular E- and F1-layer MUF should be included in a

computer program for use of the predictions in high frequency radio communication. Information on these and other aspects of ionospheric radio propagation, and assistance on computer programs for specific propagation problems may be obtained by writing to the Central Radio Propagation Laboratory. Predicted numerical map coefficients for the F2 layer in the form of a tested set of IBM punched cards or listings may be obtained by special arrangement.

The term "numerical map," is used to denote a function, $\Gamma(\lambda, \theta, t)$, of three variables (latitude (λ), longitude (θ) and time (t)) which represents, in our case, the world-wide geographic and diurnal variations of an ionospheric characteristic. The definitions and ranges of the independent variables are:

$$\lambda = \text{geographic latitude}, \qquad -90° \leqq \lambda \leqq 90° \qquad (2.1)$$

$$\theta = \text{geographic longitude}, \qquad 0° \leqq \theta \leqq 360° \qquad (2.2)$$

(θ in degrees east of Greenwich)

$$t = \text{local mean hour angle:} \quad -180° \leqq t \leqq 180° \qquad (2.3)$$

$t = (15h - 180°)$, where h = local mean time (LMT) in hours.

Universal time (UT) may be introduced by the relation,

$$T = t - \theta, \qquad -180° \leqq T \leqq 180° \qquad (2.4)$$

where T is the Greenwich hour angle.

The general form of $\Gamma(\lambda, \theta, t)$ is the Fourier time series,

$$\Gamma(\lambda, \theta, t) = a_0(\lambda, \theta) + \sum_{j=1}^{H}(a_j(\lambda, \theta) \cos jt + b_j(\lambda, \theta) \sin jt) \qquad (2.5)$$

where H denotes the number of harmonics retained to represent the diurnal variation. The Fourier coefficients, $a_j(\lambda, \theta)$ and $b_j(\lambda, \theta)$, which vary with the geographic coordinates, are represented by series of the form

$$\sum_{k=0}^{K} D_{sk} G_k(\lambda, \theta) \qquad (2.6)$$

where the $G_k(\lambda,\theta)$ are given in Table 3. The index s denotes which Fourier coefficient is represented, in the order given by

$$s=2j \text{ for } a_j(\lambda,\theta), \qquad j=0, 1, \text{--------}, H$$
$$s=2j-1 \text{ for } b_j(\lambda,\theta), \qquad j=1, 2, \text{--------}, H \qquad (2.7)$$

A numerical map, $\Gamma(\lambda, \theta, t)$ is completely defined by a relatively small table of coefficients, D_{sk} . Table 1 presents the coefficients defining the function $\Gamma(\lambda, \theta, t)$ for monthly median foF2 observed for December 1958. Table 2 presents the coefficients for monthly median F2-M3000 observed for December 1958. The graphical maps of Figures 1 to 12 and 15 to 18 were derived from these coefficients. Thus, these examples were made using coefficients derived directly from observed data, rather than predicted coefficients.

It is important that all coefficients be used in computing values of the function $\Gamma(\lambda, \theta, t)$. Since the functions $G_k(\lambda,\theta)$ are not orthonormal relative to the coordinates (λ_i, θ_i) of the ionosphere stations providing the basic data, a correct lower degree approximation to $\Gamma(\lambda, \theta, t)$ cannot be obtained by dropping higher order terms of the series (2.6) [Jones and Gallet, 1962a, 1962b].

3. GRAPHICAL PREDICTION MAPS

The graphical prediction maps of the new CRPL series were derived from the predicted numerical maps described in Section 2 [Jones and Gallet, 1962b] . The contours of F2-Zero-MUF and F2-4000-MUF were calculated by computer and plotted on the base maps. It is important to keep in mind the distinction between these prediction maps and the charts of the earlier type of prediction. These prediction maps are world maps with contours of the predicted parameter drawn on the reference grid of latitude and longitude, each map representing the variations of the parameter over the world at a given hour of Universal Time (UT). The former zone charts, although looking like maps, were time charts with contours of the predicted parameter drawn on a reference grid of latitude and local time (LT), each chart representing the average diurnal variation of the parameter within the zone.

The graphical prediction maps give, for each even hour of Universal Time (GMT or UT), values of predicted F2-Zero-MUF and predicted F2-4000-MUF. Figures 1 to 12 are maps of these character-

istics for December 1958. The F2-Zero-MUF and F2-4000-MUF maps for the same hour appear on the same page. The values predicted are monthly medians. It should be remembered that there is considerable day-to-day variation about the monthly medians, especially on disturbed days. Areas in or near the auroral zone are particularly affected by ionospheric disturbance.

The gnomonic maps, centered on the pole, present the same predictions from 30° latitude to the pole, for 0000 and 1200 hours Universal Time. These present a less distorted picture of the shape of the contours in polar areas. Figures 15 to 18 show maps for the north and south polar regions for December 1958 made from the same data as the world maps for the corresponding time.

Regular E-layer predictions will no longer appear in the monthly predictions. Instead, E-layer 2000-MUF predictions are obtained by use of the nomogram of Figure 22, together with the appropriate monthly chart of solar zenith angle, Figures 23 through 34. The E-MUF for shorter distances is obtained from the nomogram of Figure 40.

F1-layer ionization depends upon solar zenith angle in much the same way as E-layer ionization. Therefore, F1-layer maximum usable frequencies are approximated by a distance extension of the nomogram of Figure 40.

Sporadic-E predictions are not included in the new version of the CRPL series. Numerical maps of sporadic-E data are being prepared. When completed, sporadic-E predictions will be issued in forms compatible with the F2-layer predictions. Until these are available, sporadic-E prediction charts of the CRPL-D series issued before January 1963 may be used, selecting the correct month from the more recent issues if Es propagation predictions are required.

The graphical prediction maps are prepared using Universal Time (UT), defined as the local mean time at the Greenwich (zero longitude) meridian. Therefore, if local or standard time is desired, transformation must be made after the prediction calculations are completed.

4. SOME NOTES ON IONOSPHERIC RADIO PROPAGATION

Since ionospheric radio propagation is very complex and this handbook assumes a simplified theory, it is necessary to call attention to limitations of the predictions and to other complicating factors. More detailed discussion of these and other aspects may be found in the publications noted in the reference list. [Brown, et al., 1963; Budden, 1961; Mitra, 1952; Ratcliffe, 1960; Rawer, 1957].

A. MAXIMUM USABLE FREQUENCY (MUF) AND OPTIMUM WORKING FREQUENCY (FOT)

The Maximum Usable Frequency (MUF) is defined as the highest frequency for ionospheric transmission over a given path. The MUF will vary as ionospheric conditions over the path change. The "classical" MUF is the highest frequency for transmission by ionospheric refraction alone. The "standard" MUF is an approximation to the "classical" MUF and is derived from vertical incidence ionosphere observations by use of the standard international transmission curve or its equivalent. The "operational" MUF tends to exceed the "classical" MUF as a consequence of propagation path changes resulting from ground and/or ionospheric scatter and horizontal ionization gradients. Since the present state of the art does not permit convenient inclusion in manual prediction calculations of many complications, such as scatter, on a routine basis, the new CRPL predictions include only "standard" MUF as an approximation to the "classical" MUF. For longer distances, the two control point standard MUF approximation is used, which usually gives a higher value than the standard MUF based on a multi-hop model of the propagation path, and corresponds more closely to operational experience.

The F2 layer of the ionosphere is quite variable, the greatest deviations from "normal" usually occurring during ionospheric storms. Predictions of MUF are made for the monthly median value, which is the value equalled or exceeded 50% of the days during the month at a specified time of day. A fair practical approximation to the distribution of F2-MUF around the monthly median can be made by assuming that the percentage deviations are normally distributed around the median, with values 15% above and below the median being exceeded, respectively, 10% and 90% of the days during the month. The Optimum Working Frequency (FOT) is defined as the value of MUF equalled or exceeded 90% of the days during the month. (The international abbreviation, FOT, is formed from the initial letters of the French words for Optimum Working Frequency, "Fréquence Optimum de Travail".) The FOT for F2-layer propagation may therefore be estimated by multiplying the monthly median MUF by

0.85. Since the day-to-day variations of E-layer MUF and F1-layer MUF can be considered negligible for operational use, the FOT for the E and F1 layers is considered to be the monthly median MUF.

B. PROPAGATION PATHS. HOPS. REFLECTION POINTS

A propagation path is a particular route by which radio energy may travel between the transmitting and receiving antennas. More than one propagation path is often possible for a particular operating frequency and circuit. Usually, the longer the distance and the lower the operating frequency below the MUF, the greater are the number of possible paths. Since the effective distance traveled by the radio waves is different for each path, the signals arriving by the different paths may interfere with each other at the receiver. These multi-path effects, which cause serious difficulties for such applications as high speed telegraph or teleprinter circuits, can be minimized by operation as close to the MUF as possible. Operation at as high a frequency as possible also minimizes absorption effects. Since antenna characteristics of both transmitter and receiver may discriminate against, or favor, one path over another, suitable antenna design can help to reduce multi-path difficulties, but the variability of the ionosphere precludes, in practice, their entire elimination by this means.

A particular propagation path may be pictured as consisting of one or more hops, or successive reflections between the ionosphere and ground, between the transmitter and receiver. Depending on frequency, the length of a hop and the angles of departure and arrival are determined by such geometrical considerations as the effective height of the reflecting layer at the point of reflection. In applying these predictions, it is usually assumed that the ionosphere is concentric with the earth and that propagation takes place along a great circle. For average heights of the ionospheric layers, 4,000 kilometers is about the maximum great circle distance for one-hop F2-layer, for low ray propagation, and 2,000 kilometers is about the maximum for one-hop E-layer propagation. Large horizontal gradients of ionization (which are, effectively, tilts of the ionosphere) often exist and may cause large deviations from the simple model assuming a concentric ionosphere. Depending on the orientation of the path with respect to these gradients, a single F2-layer hop may vary from less than 3,500 kilometers to more than 10,000 kilometers, the longer hops involving two or more ionospheric reflections without intermediate ground reflection. The operational MUF may vary markedly from the standard MUF under these conditions. Large gradients of this type are found regularly across the sunrise-sunset line and in north-south propagation across equatorial regions,

but occasionally may occur anywhere. For applications where these effects are important, more basic ionospheric data and elaborate calculations are necessary.

C. CONTROL POINTS. THE TWO CONTROL POINT METHOD

As the number of hops in a single path and the number of possible paths increase, the detailed analysis of ionospheric propagation for a given circuit becomes impractical by manual methods. Simplifying assumptions, however, work fairly well for most applications. In the MUF calculation for distances up to 4,000 kilometers, one-hop F2-layer propagation with the point of reflection at the mid-point of the path is assumed. Since the characteristics of the ionosphere at the point of reflection affect the MUF, that point is called a "control point." Maximum one-hop E-layer propagation distance is taken to be 2,000 kilometers. During the day time, particularly in the summer and during periods of low solar activity, the regular E-F1-layer MUF (for longer distances) is often higher than the F2-MUF.

For distances beyond 4,000 kilometers, a two control point method is used. This method assumes: (1) that there are F2-layer control points on the great circle 2,000 kilometers from each terminal and E-layer control points on the great circle 1,000 kilometers from each terminal; (2) ionospheric conditions at the control points determine the frequencies that can arrive at or leave the respective terminals; (3) the highest frequency which can be propagated over the circuit (the MUF) is approximated by the highest frequency which can arrive at or depart from both terminals.

Experience indicates that the two control point method, which ignores the details of propagation between the control points, provides a useful approximation for ionospheric effects which tend to increase the MUF, (e.g., scatter, ionospheric tilts, and the high angle, or Pedersen ray), since this method tends to make the MUF higher than that predicted in terms of an integral number of hops, each less than or equal to the maximum distance for a single hop.

For very long circuits it is often advisable to consider propagation along both the short and the long arcs of the great circle. When the transmitter and receiver are almost antipodal, propagation is often observed over a wide range of directions, not necessarily along the great circle, varying with time of day, season, and frequency.

For certain distances and operating frequencies, ionospheric conditions may permit propagation by both one-hop and two-hop paths. If the antenna pattern or the terrain cut off the low ray for the one-hop path (a low angle of take-off), a gap may be observed between the frequencies that can be propagated by the two-hop path and the high ray of the one-hop path. This is an exception to the usual assumption that all frequencies below the MUF can be propagated along the path. The regular E layer and sporadic E may also, under certain conditions, cut off particular propagation paths for frequencies that might otherwise be supported by the F layer. For reasons such as these, a detailed path analysis may yield more satisfactory results than the two control point method in cases where one-, two- or three-hop paths are possible.

D. IONOSPHERIC DISTURBANCE

The predictions described in this handbook are for average conditions expected within the month. At present, it is not possible to predict the day-to-day variations of the ionosphere. However, the FOT methods allow approximately for the normal variations expected during the month. Larger departures from normal may occur during ionosphere storms and may require substantial changes in operating frequency to maintain communications. Even with these changes, operation is often difficult or impossible, the difficulties being most severe for paths passing through or near the auroral zones. The CRPL Radio Warning Services provide various forecasts of ionosphere disturbances, permitting operators to clear urgent traffic and prepare to make the necessary frequency shifts to keep communication circuits in operation during the disturbance.

E. INDEX OF SOLAR ACTIVITY

A fundamental relationship used in radio propagation predictions is the observed correlation between ionospheric characteristics and solar activity. An important source of error is the uncertainty in predictions of solar activity. The smoothed Zurich sunspot number has proved useful as an index of solar activity for ionospheric variations and predictions, and is still in use. Studies of other indices of solar activity are in progress. If another index of solar activity proves more useful than the sunspot number, it will be adopted. A change in index of solar activity would require no basic change in the format or application of these predictions.

F. ABSORPTION. NOISE. LOWEST USEFUL FREQUENCY

Although the MUF and FOT represent important aspects of ionospheric radio propagation and for many purposes provide sufficient information, it is also important in many applications to have estimates of the power available at the receiving antenna and of the available signal-to-noise ratio. To be useful, the received signal level must be sufficiently above both natural and man-made noise. As the operating frequency is decreased, the available signal power normally decreases and the noise power increases, resulting in a lower available signal-to-noise ratio until a lowest useful frequency (LUF) results. Transmitter power, antenna gain, and the type and quality of radio service required are important elements in determining the LUF of a circuit. Methods for determining the LUF at various times are described elsewhere [Brown, et al., 1963] . Consideration of the LUF, as well as the MUF and FOT, is important in design of equipment for high frequency communication circuits, in frequency allocations, and in efficient use of assigned frequencies.

G. CHOICE OF OPERATING FREQUENCIES

In general, frequencies are selected between the LUF and FOT. Best results are usually obtained by operating as close to the FOT as possible. Operation above the FOT increases the probability of propagation failure due to skipping (penetration through the ionosphere) and operation at too low a frequency normally results in weak reception due to excessive absorption and high radio noise levels. Because of the diurnal variation of the ionosphere, a single frequency is usually insufficient for twenty-four-hour operation, and two or more frequencies are necessary. Each frequency is a compromise between the best single frequency to use over a specified part of the day for that circuit and the requirements of other services for frequencies in that portion of the radio spectrum. A different frequency complement is often necessary for different seasons and different phases of the solar activity cycle. Propagation characteristics such as vertical angles and optimum frequencies should be considered in antenna selection. Best results are often obtained when the antenna is specifically designed for the most favorable propagation path and operating frequency.

5. DETERMINING GREAT-CIRCLE DISTANCES AND LOCATING TRANSMISSION CONTROL POINTS

Figure 13 is a map of the world on a modified cylindrical projection of the same size and scale as the maps appearing monthly in the CRPL predictions. An area 10° in latitude by 15° in longitude appears as a square with a side of 0.6 cm, which has the same proportion of latitude to longitude as that recommended by the C.C.I.R. The scale recommended by the C.C.I.R. is 1 cm for 10° latitude and 15° longitude. The distortion in this map is greatest at the poles. The earth is assumed to be a sphere of 40,000 kilometers circumference, the error being negligible in most radio propagation problems. Figure 14 is a chart to the same scale as Figure 13, indicating great circles on the surface of the earth (solid lines). Because of the symmetry of the sphere, the set of great circles crossing the equator at two points 180° apart can be used for any great circle. Distances, in thousands of kilometers, are indicated by the numbered dot-dash lines crossing the great circles, while the intermediate dotted lines show 500-kilometer intervals.

Figures 19 and 20 are, respectively, gnomonic projection maps of the north and south polar areas, from latitude 30° to the pole. The plane of projection is tangent at the pole. The distortion of these maps is greatest at their peripheries. Figure 21 is a great-circle chart for the polar gnomonic projection maps. As in the world map great-circle chart, solid lines are great circles, distances in thousands of kilometers are indicated by the numbered dot-dash lines, and the dotted lines show 500-kilometer intervals.

The great circle charts may be used to obtain great circles graphically, measure distances, and determine the location of "control points," proceeding by the following steps:

A. FOR WORLD MAPS

1. Prepare a transparency by placing a piece of transparent paper or suitable plastic over the map, Figure 13. Draw the equatorial line (zero degrees latitude), the Greenwich meridian (zero degrees longitude), and any other reference meridians desired. (It is often useful to mark the reference meridians for the time zones of the path end points.) Place dots over the two terminal locations of the transmission path, marking one end A, and the other end B.

2. Place the transparency over the great circle chart, Figure 14. Keeping the equatorial line of the transparency on the equatorial line of the great circle chart, slide the transparency horizontally until the terminal points, A and B, fall either on the same great circle or are at the same proportional distance between adjacent great circles.

3. The length of transmission path is determined from the dot-dash lines, numbered in thousands of kilometers from the center of the system of great circle curves, and the intermediate dotted curves, indicating 500-kilometer intervals. Halfway point and "control points" may be measured off by the distance scale and their position marked on the transparency.

B. FOR POLAR MAPS

1. Prepare a transparency by placing a piece of transparent paper or suitable plastic over the desired map, Figure 19 or 20. Mark the pole by drawing the Greenwich meridian (zero degrees longitude), the 180° meridian, the 90° E and the 90° W meridians. (These form two straight lines intersecting at the pole at right angles.) Note that Greenwich meridian points down and East longitude is read counter-clockwise for the North polar map, while the Greenwich meridian points up and East longitude is read clockwise for the South polar map. Any other reference meridians desired may also be drawn.

2. Place dots over the two terminal locations of the transmission path, marking one end of the path A and the other end B. Connect A and B with a straight line. (Note: Any straight line on a gnomonic projection is a great circle on the sphere.)

3. Place the transparency over the great circle distance chart for the polar gnomonic maps, Figure 21. Keeping the pole of the transparency over the pole of the great circle chart, rotate the transparency until the line joining the terminals A and B is parallel to the straight lines (great circles) of the chart. The length of the transmission path is determined from the dot-dash curves numbered in thousands of kilometers and the intermediate dotted curves indicating 500-kilometer intervals. Halfway point and "control points" may be scaled off and marked on the transparency.

Examples of transmission paths are marked on the maps, Figures 35 and 37, and are also shown on the corresponding great circle charts, Figures 36 and 38. These paths are used in the illustrative problems worked out later in this manual.

6. CALCULATION OF MUF AND FOT (PROPAGATION BY E- AND F-LAYERS)

A. DISTANCES UP TO 4,000 km (SHORT DISTANCES)

1. Prepare a transparency for the transmission path as described in Section 5, marking the end points, great circle and halfway point. Note the path length.

2. Place the great circle transparency over each F2-Zero-MUF map, Figures 1A to 12A, taking care to superpose accurately the equator and reference meridian lines on their corresponding lines on the map. Read and tabulate the values of F2-Zero-Muf at the halfway point for each map.

3. In the same way, read and tabulate F2-4000-MUF at the halfway point for each map, Figures 1B to 12B.

4. Obtain F2-MUF for the transmission path from the distance interpolation nomogram, Figure 39, by placing a straight edge between values of F2-Zero-MUF (left hand scale) and F2-4000-MUF (right hand scale) for the same Universal Time (UT). Read and tabulate the MUF at the intersection of the straight edge with the appropriate vertical distance line, interpolating between the oblique lines.

5. Select the chart of the sun's zenith angle for the appropriate month, Figures 23 to 34. Superpose the transparency on the zenith angle chart, carefully aligning the two equators. Place the Greenwich meridian of the transparency on the 00 local time line of the chart and, at the halfway point, read the sun's zenith angle at 00 UT. Place the Greenwich meridian of the transparency on the 02 local time line of the chart for the zenith angle at 02 UT, and so on for each even hour local time line, to obtain and tabulate values of the sun's zenith angle for each two hours UT. It may prove convenient to use another meridian line on the transparency for reference for part of the readings, taking care to make the proper time conversion. For example, using the 180° meridian as reference, add 12 hours to convert to UT.

6. Obtain the E-2000-MUF by laying a straight edge across the E-layer 2000-MUF nomogram, Figure 22, between the sun's zenith angle (left hand scale) and the predicted sunspot number (right hand scale) obtained from the monthly predictions. The E-2000-MUF is read at the intersection of the straight edge with the diagonal scale. Tabulate.

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7. Convert the E-2000-MUF to E-MUF for the transmission path by the nomogram of Figure 40. Lay a straight edge between the E-2000-MUF (left hand scale) and the path length, in kilometers, (distance, right-hand scale), reading the E-MUF at the intersection of the straight edge with the center scale of nomogram. This nomogram includes a factor for Fl-propagation between 2,000 and 4,000 kilometers, and the MUF values tabulated in this step therefore include allowance for the Fl-MUF. Tabulate.

8. The MUF for the transmission path is the higher of the two MUF values, comparing the F2-MUF obtained in step 4 with the E-MUF obtained in step 7. Tabulate the higher of the two.

9. Convert the F2-MUF for the transmission path, from step 4, to F2-FOT either by multiplying the F2-MUF by 0.85 or by using the conversion scale at the extreme right of Figure 39. Tabulate.

10. To obtain the FOT, compare the F2-FOT from step 9, with the E-MUF from step 7. The higher of the two is the FOT for the transmission path. (Note: Because the E and Fl layers show relatively little day-to-day variation, for practical purposes the E-Fl-FOT is the same as the E-Fl-MUF.)

B. DISTANCES GREATER THAN 4,000 km (LONG DISTANCES)

The following procedure is based on the two control point method.

1. Prepare a transparency as described in Section 5, marking the end points, A and B, the E-layer control points, A' and B' (1,000 km from their respective terminals), and the F2-layer control points, A'' and B'' (2,000 km from their respective terminals). Note the distance. For very long distances it is often advisable to consider both the "short route" (minor arc of the great circle) and the "long route" (major arc).

2. Place the great circle transparency over each F2-4000-MUF map, Figures 1B to 12B, superposing the equator and reference meridian lines on the corresponding lines on the map. For each F2 control point, A'' and B'', read and tabulate the F2-4000-MUF.

3. Select the chart of the sun's zenith angle for the appropriate month, Figures 23 to 34. Superpose the transparency on the zenith angle chart, aligning the two equators. In the same manner as for the short path calculation, place the Greenwich meridian of the transparency on the 00 local time line of the chart. Read the zenith angle at each E

control point, A' and B', for 00 UT. Place the Greenwich meridian of the transparency on the 02 local time line of the chart and read the zenith angle for 02 UT. Repeat, displacing the transparency to superpose its Greenwich meridian on each even hour local time line, tabulating the sun's zenith angle for each of the E control points, A' and B', for each even hour UT. It may prove convenient to use another reference meridian line on the transparency for part of the readings, making the proper time conversion, as for short distances.

4. As for short distances, obtain the E-2000-MUF for each E control point by laying a straight edge across the E-layer 2000-MUF nomogram, Figure 22, between the sun's zenith angle (left hand scale) and the predicted sunspot number (right hand scale) obtained from the monthly predictions. The E-2000-MUF is read at the intersection of the straight edge with the diagonal scale. Tabulate the E-2000-MUF for each E control point, A' and B'.

5. For each terminal, compare the F2-4000-MUF (from step 2) with the E-2000-MUF (from step 4). The MUF for a terminal is the higher of the two MUF's at its corresponding E and F control points. Tabulate the MUF for terminals A and B.

6. The transmission path MUF is the lower of the MUF's for the two terminals A and B. Tabulate.

7. Convert the F2-4000-MUF (from step 2) to F2-4000-FOT for each terminal either by multiplying by 0.85 or by using the conversion scale at the extreme right of Figure 39. Tabulate for each F2 control point, A'' and B''.

8. For each terminal, compare the F2-4000-FOT for F2 control points, A'' and B'', with the E-2000-MUF for the corresponding E control points, A' and B'. The higher value of each pair is the FOT for that terminal, respectively A and B. Tabulate the FOT for each terminal. (See steps 7 and 10 of the short distance calculation for reasons why E-2000-MUF is also taken as E-2000-FOT. Note also that the E-2000-MUF includes a correction to take account of F1-layer propagation.)

9. The transmission path FOT is the lower of the FOT's for the two terminals, A and B. Tabulate.

7. INCLUSION OF SPORADIC - E (Es) PROPAGATION

The mechanism of sporadic-E (Es) propagation is not well understood. However, it is known that sporadic-E propagation is often possible at frequencies above the MUF for regular E- or F2-layer propagation, and should be considered in predicting the MUF and FOT.

Until the numerical map version of Es predictions becomes available, it is recommended that use be made of a recent Es prediction chart selected for the appropriate month from the D series issued before January 1963. Instructions for the use of these charts are given in NBS Circular 465, "Instructions for the Use of Basic Radio Propagation Predictions."

8. EXAMPLES

Tables 4, 5 and 6 and Figures 41, 42 and 43 present examples of detailed path predictions made by reading the basic F2 data from the sample maps, Figures 1 to 12, and applying the manual methods described in this handbook. One short and two long transmission paths are worked out. The great circle transmission paths are marked both on the world map, Figure 35, and the corresponding great circle chart, Figure 36. Although not used for the calculations, the same transmission paths are shown on the north polar area map, Figure 37, and the corresponding great circle chart, Figure 38. (The Buenos Aires to Berne path runs off the edge of the polar map).

The twelve month moving average Zurich sunspot number for December 1958 was 180, and was near the maximum of the solar activity cycle. The F2 and E-F1 MUF and FOT were worked out in detail for the examples. Although F2-propagation was controlling at all times in these examples, E-F1 propagation is often important, particularly in the summer at low solar activity, and should be calculated. The form used for tabulating the prediction calculations may be modified to suit the problem at hand, e.g., additional columns may be added to include Es propagation and various phases of LUF calculations [Brown, et al., 1962].

The reader is advised to carry out the map reading and prediction computations for these examples. Repeated independent readings will give an idea of the variations in judgment expected in reading the maps.

The predicted MUF and FOT values for these transmission paths were found to be in good agreement with the more precise values obtained by machine computation. Operating frequencies should be chosen as near the FOT as possible, within the limitations of frequency assignments.

Example 1. Short Distance. Table 4, Figure 41.

A_1, Washington (39° N, 78° W), to B_1, Ottawa, (45° N, 76° W)
Distance: 750 km
Predictions were read at the halfway point, M, indicated on Figures 35 and 36.

Example 2. Long Distance. Table 5, Figure 42.

A_2, Washington (39° N, 78° W to B_2, Berne (47° N, 7° E)
Distance: 6,700 km
Predictions were read at the control points, A'_2, A''_2, B'_2, and B''_2, indicated on Figures 33 and 36. This transmission path was entirely in the northern hemisphere.

Example 3. Long Distance. Table 6, Figure 43.

A_3, Buenos Aires (35° S, 59° W), to B_3, Berne (47° N, 7° E)
Distance: 11,200 km
Predictions were read at the control points A'_3, A''_3, B'_3, and B''_3, indicated on Figures 35 and 36. This transmission path crossed the equator.

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TABLE I

TIME VARIATION

Harmonic		0	1		2		3		4	
GEOGRAPHICAL VARIATION	K \ S	a	1	2	3	4	5	6	7	8
I	0	1.0975529E 01	1.7027571E 00	1.4862860E 00	-7.5606564E-01	7.6257150E-01	-2.7180890E-01	-5.5354336E-01	1.8953986E-01	-2.1906067E-01
	1	-1.7012024E 00	1.6448708E-01	2.5329333E 00	-2.7034453E 00	1.8156968E-01	-1.4224915E 00	-2.3583061E 00	-3.3616213E-01	-9.5059532E-01
	2	4.2770728E 00	9.3584328E 00	3.8619406E 00	-2.0455995E 00	-1.1351002E 00	1.0673727E 00	-6.8313993E-01	2.0678045E 00	-1.9993110E 00
	3	2.2543303E 01	3.4320387E 01	-1.4448591E 01	1.7676342E 01	2.6415675E 00	7.1083783E 00	1.6761376E 01	8.5148646E 00	4.6742557E 00
	4	-8.7023281E 01	-8.9283786E 01	5.0441217E 01	1.8679793E 01	7.7832181E 00	-7.9094652E 00	9.4932253E 00	-1.4594041E 01	1.4835242E 01
	5	-1.2697548E 02	-2.1021881E 02	1.0850153E 02	-4.3286481E 01	-2.1369857E 01	-2.5611759E 01	-4.9815283E 01	-3.6448317E 01	-1.6058546E 01
	6	3.3194980E 02	2.6762136E 02	-3.0061563E 02	-6.8039322E 01	-2.9353597E 01	4.2629441E 00	-2.3926843E 01	2.1681693E 01	-3.4825963E 01
	7	2.9398724E 02	4.9989017E 02	-2.5305406E 02	6.6123591E 01	6.7410372E 01	3.4701817E 01	7.2922651E 01	5.0152924E 01	2.5685517E 01
	8	-6.2864316E 02	-3.7050085E 02	6.5117434E 02	1.4214614E 02	6.2977137E 01	3.0199225E 01	1.9111568E 01	-4.2070195E 00	3.2328641E 01
	9	-2.9553332E 02	-5.1807641E 02	2.4061109E 02	-5.5248716E 01	-7.5580178E 01	-8.2885423E 00	-4.8029592E 01	-2.1621980E 01	-1.6334149E 01
	10	5.7812739E 02	2.4288284E 02	-6.3014296E 02	-1.4026740E 02	-6.3059824E 01	-4.3739870E 01	8.8887490E 00	-8.4759525E 00	-6.2703856E 00
	11	1.0728381E 02	1.9451654E 02	-8.4266973E 01	1.7395313E 01	2.6734065E 01	-6.5989668E 00	1.0488517E 01	-3.2576519E-01	2.9815755E 00
	12	-2.0465868E 02	-6.1672124E 01	2.2402565E 02	5.0565827E 01	2.2056101E 01	1.6441509E 01	-1.2472386E 01	3.2337783E 00	-3.9441097E 00
II	13	1.8253447E-01	-3.0897393E-01	-1.7134542E-01	-6.8267239E-02	2.2101744E-01	1.2034706E-01	6.3879483E-02	9.8065099E-03	-2.9474481E-02
	14	-2.7817490E-01	-2.4616947E-01	-5.2836371E-01	7.9224710E-01	-1.9317761E-01	-1.0721080E-01	2.2021524E-01	-8.8178408E-02	-4.4758748E-02
	15	-4.4723618E-01	-1.1510026E 00	-2.0885526E-01	6.7929192E-01	1.5771487E 00	2.1633874E-01	1.2504549E-01	3.8882741E-01	3.1735651E-01
	16	-4.1717904E 00	-8.3497413E 00	2.7795444E 00	2.5485381E 00	-5.8212114E-01	-2.2192447E 00	8.0045419E-02	-3.2292146E-01	-2.7617327E-02
	17	-9.1404111E 00	-6.1804596E-01	4.5093232E 00	-6.9523931E-01	-6.9972273E 00	-4.6429499E 00	-9.8506230E-01	-6.6326894E-02	1.1306202E 00
	18	1.2242684E 01	7.0345864E 00	-1.0043306E 01	-1.3412635E 01	1.7224812E 01	4.6672130E 00	-1.3309710E 00	1.6479981E 00	7.7601019E-03
	19	1.0127541E 01	1.5802478E 01	-1.0402084E 01	3.1921534E-01	-3.0087138E 01	-2.7518425E-01	6.0082695E-01	-6.2766758E 00	-1.8810184E 00
	20	1.3692289E 02	1.6502871E 02	-7.2863230E 01	-4.6039071E 01	1.6797187E 01	2.6934572E 01	-2.9434578E 00	4.0602687E 00	-6.7998774E-01
	21	6.1376760E 01	2.3823115E 01	-2.9387898E 01	1.3798739E 01	4.5257363E 01	3.3083965E 01	2.2576369E 00	4.9560452E-03	-7.0812981E 00
	22	-7.5134997E 01	-4.0703020E 01	1.2722517E 02	7.3901458E 01	-2.1298590E 02	-6.0032408E 01	4.1048784E 00	-5.3080921E 00	-4.4847116E-01
	23	-4.2678511E 01	-5.7403102E 01	6.3441706E 01	-1.0699640E 01	1.8860612E 02	3.9099306E-03	-1.3549511E 01	2.7534093E 01	2.9763668E 00
	24	-7.3474996E 02	-8.3832042E 02	4.6625933E 02	2.7487080E 02	-1.0501047E 02	-9.7848264E 01	1.7680123E 01	-1.0423073E 01	4.6347538E 00
	25	-1.3542068E 02	-9.5678871E 01	1.1218257E 02	-6.0150149E 01	-1.1361036E 02	-9.4025106E 01	-6.5297469E 00	2.5356720E-01	2.2912621E 01
	26	1.3588736E 02	7.0017204E 01	-4.1588927E 02	-2.2190408E 02	1.0106682E 03	2.9822517E 02	-1.8746828E 01	5.4490803E 00	2.2811089E 00
	27	6.6506710E 01	7.3650686E 01	-1.5071120E 02	2.7581728E 01	-4.8708670E 02	-2.3170511E 00	4.2250249E 01	-4.3925300E 01	-2.3007317E 00
	28	1.6004726E 03	1.7165541E 03	-1.1943014E 03	-6.8555969E 02	2.6207012E 02	1.4589258E 02	-4.5178688E 01	7.0483167E 00	-1.2840969E 01
	29	1.2941161E 02	1.6905857E 02	-2.2417788E 02	1.1161972E 02	9.7296709E 01	1.2551122E 02	2.2378222E 01	-1.0174850E-01	-4.3421563E 01
	30	-1.4560894E 02	-2.1773458E 01	5.3643370E 02	3.4252456E 02	-2.1809547E 03	-6.5665503E 02	4.7150726E 01	-1.5946963E 00	-4.0316450E 00
	31	-3.6146227E 01	-2.2681355E 01	1.5252939E 02	-3.3499210E 01	5.5134596E 02	4.7428764E 00	-4.8291029E 01	2.2951577E 01	1.6601351E 00
	32	-1.5217490E 03	-1.5434575E 03	1.3184717E 03	7.4570659E 02	-2.8001628E 02	-9.8419338E 01	4.9689458E 01		1.5125651E 01
	33	-7.6340763E 01	-1.5396956E 02	2.0957641E 02	-9.2436357E 01	1.9322647E 01	-7.2318683E 01	-3.1349616E 01		4.1260099E 01
	34	1.1984987E 02	-1.9887089E 01	-2.1895422E 02	-2.3280115E 02	2.1513221E 03	6.5328470E 02	-5.0107861E 01		2.8144535E 00
	35	2.5633815E 00	-8.9765286E 00	-5.5255212E 01	1.4662282E 01	-2.2688478E 02	-2.8998729E 00	1.9715753E 01		-4.2475979E-01
	36	5.2219397E 02	5.0781178E 02	-5.2367100E 02	-2.9317565E 02	1.0722054E 02	2.6733115E 01	-1.9521694E 01		-6.3189466E 00
	37	3.3476701E 01	5.7096434E 01	-7.4110801E 01	2.7676970E 01	-4.3072069E 01	1.1099980E 01	1.4804017E 01		-1.4512384E 01
	38	-4.8817652E 01	2.5019247E 00	-1.9992678E 01	4.9954472E 01	-7.8687621E 02	-2.3962078E 02	1.8999020E 01		-6.3592226E-01
III	39	-6.9022242E-03	-2.3726618E-02	-3.3863767E-01	2.4150787E-01		1.1883768E-02	4.9183183E-02		6.0306707E-03
	40	2.3235672E-02	1.5689547E-01	-1.3921852E-01	8.4346702E-02		-6.4377151E-02	9.8777164E-02		-3.9878624E-02
	41	2.4512497E-02	-1.0729051E-02	2.5190540E-01	-4.0894723E-02		3.0240182E-03	2.9543621E-02		2.7270377E-03
	42	-5.6014360E-01	1.0909216E-01	-1.6336312E-01	1.3507879E 00		-4.9721892E-02	4.4322262E-02		-2.7728304E-02
	43		2.6653873E-01	5.4411260E 00	-3.6560385E-01		-2.3472665E-01	-3.5234130E-01		-6.7747008E-02
	44		-2.4129488E 00	4.8272459E 00	-1.6109489E 00		1.8468230E 00	-5.9923277E-01		6.1330695E-01
	45		-2.2568523E-02	8.4226443E-01	2.9548098E-01		3.9690866E-02			5.7363140E-03
	46		-3.1946334E-01	1.2057742E 00	-5.6112505E 00		3.5356301E-01			8.1199026E-02
	47		-4.0274389E-01	-1.7344368E 01	-3.4528911E-01		7.9117051E-01			1.0236671E-01
	48		4.1000685E 00	-1.9582226E 01	2.7032396E 00		-7.3707471E 00			-1.0421276E 00
	49			-1.1247104E 00	-4.2169459E-01		-7.9710127E-02			
	50			-1.5741791E 00	6.5178954E 00		-4.4173399E-01			
	51			1.6668546E 01			-7.2557599E-01			
	52			1.8444390E 01			6.9247085E 00			

Harmonic		5		6		7		8	
GEOGRAPHICAL VARIATION	K \ S	9	10	11	12	13	14	15	16
I	0	1.9667511E-01	2.4664364E-01	-9.6199269E-02	9.6732820E-02	-8.4860413E-02	-9.1234739E-02	6.5003374E-02	-2.0512594E-02
	1	3.8972554E-01	-8.4171342E-03	1.8619000E-01	2.0956517E-01	-7.9410625E-02	5.2109727E-02	-8.0547124E-02	-5.5247232E-02
	2	-4.4712581E-01	-1.2903891E 00	6.1299201E-01	-3.3489200E-01	2.9654734E-01	5.2667627E-01	-3.5176336E-01	2.5616074E-02
	3	-5.0140063E-01	-6.5880308E-02	-2.1470110E-01	-2.8893537E-01	9.4174408E-02	-6.6127658E-02	1.2508225E-01	6.7799408E-02
	4	1.9107307E-01	1.0919535E 00	-5.7498534E-01	2.2332078E-01	-2.1764221E-01	-4.8065190E-01	3.4288950E-01	

I - Main latitudinal variation. Mixed latitudinal and longitudinal variation: II - First order in longitude, III - Second order in longitude.

Notation: For each entry the number given by the first eight digits and sign is multiplied by the power of ten defined by the last two digits and sign.

COEFFICIENTS D_{SK} DEFINING THE FUNCTION $\Gamma(\lambda,\theta,t)$ FOR MONTHLY MEDIAN f_0F2 (Mc/s)

DECEMBER 1958

TABLE 2

TIME VARIATION

Harmonic		0	1		2		3	
GEOGRAPHICAL VARIATION	K \ S	0	1	2	3	4	5	6
I	0	2.4597045E 00	-2.7864561E-01	-2.0356853E-01	2.3461928E-02	-7.6179242E-02	3.2068893E-02	-3.2689627E-02
	1	3.6954687E-01	-1.8391149E-02	-1.2754253E-01	-1.5806746E-01	8.4492028E-02	-1.2135339E-01	-8.3882467E-02
	2	1.7629436E 00	8.8885969E-01	9.5534980E-01	-4.6495117E-01	3.3450422E-01	-4.4479275E-01	-2.4594132E-01
	3	4.4937205E-02	4.2120877E-02	8.8880715E-01	2.2096053E-01	-3.3338858E-01	2.0295892E-01	2.3496002E-01
	4	-5.4440793E 00	1.5063822E-01	-3.1809667E-01	7.0890932E-01	-1.4431769E 00	1.3843947E 00	8.6857817E-01
	5	-6.0006863E-01	1.4744394E-02	-6.3039878E-01	-1.5046852E-01	3.0635701E-01	-8.8043374E-02	-1.9979359E-01
	6	6.7451826E 00	-1.3552918E 00	-1.0804226E 00	-4.9387181E-02	2.5417657E 00	-1.9422786E 00	-5.5254013E-01
	7	3.4695590E-01	-4.5053890E-02	-1.1137213E-01	1.1862618E-01	-2.8149233E-02	2.4925547E-02	5.2938817E-02
	8	-3.0666148E 00	6.0030538E-01	6.4208925E-01	-2.1531846E-01	-1.3797404E 00	1.0119523E 00	-5.7694210E-02
II	9	7.6215219E-03	-1.4952843E-02	9.2220060E-03	1.7373093E-02	1.9521040E-03	1.2557834E-02	2.4517395E-04
	10	-8.6248538E-02	3.9951287E-03	8.9846530E-03	2.1299871E-02	-3.9493725E-02	4.6963555E-02	1.4939295E-02
	11	1.3116686E-02	-3.6824179E-02	6.2515870E-02	-6.3571962E-05	1.8724717E-02	3.5390121E-02	-1.8339332E-02
	12	-2.9158792E-01	-6.3511761E-01	-1.8566048E-01	3.5302817E-01	-2.3466288E-01	7.6185253E-03	1.3288658E-01
	13	-5.6047089E-03	1.7272247E-02	-1.7549958E-01	1.9310906E-02	-6.8180130E-03	-8.0042152E-02	1.1169360E-02
	14	5.2549593E-01	-2.7285330E-02	-6.6125242E-01	-1.5278838E-01	2.2032028E-01	-6.2597752E-01	2.7349260E-02
	15	-1.9611105E-01	-8.5644186E-03	-4.0172087E-02	1.7888334E-01	-4.3772657E-02	-1.2270745E-01	1.5044717E-02
	16	2.0560703E 00	4.6495761E 00	1.4818957E 00	-1.9121817E 00	1.6249525E 00	-1.2032531E-01	-8.5532446E-01
	17	1.0345496E-02	-9.5678610E-02	3.8659861E-01	-8.2966511E-02	5.1812095E-02	-4.5166591E-02	-2.5326822E-02
	18	1.2496830E-01	-2.4561137E-01	3.3380832E 00	-1.1601990E-01	-9.3382241E-01	3.1154308E 00	-6.3513430E-02
	19	5.0870426E-01	-3.1294876E-01	-6.1709802E-02	-3.7130666E-01	-3.7149905E-02	1.7777534E-01	-7.0192923E-03
	20	-5.1198447E 00	-9.7591153E 00	-2.7327168E 00	3.3748487E 00	-3.2455807E 00	2.2450502E-01	1.5462864E 00
	21	9.2945119E-02	-5.3925217E-02	-4.8140595E-01	1.3339700E-01	-1.9650605E-01	2.9338350E-01	1.4836907E-02
	22	-9.8967094E-01	9.2055483E-01	-6.4649473E 00	5.3845559E-01	1.1124675E 00	-5.2129884E 00	4.1918286E-02
	23	-3.4868085E-01	3.2589110E-01	7.7423149E-02	2.2646917E-01	7.1522920E-02	-1.2589389E-01	-4.2114294E-03
	24	3.5455681E 00	6.2567248E 00	1.9184216E 00	-1.9352055E 00	1.8365364E 00	-1.3177885E-01	-8.6572829E-01
	25	-1.3643478E-01	1.3335468E-01	3.4164304E-01	-5.4899275E-02	1.6122415E-01	-1.6834600E-01	
	26	5.0289852E-01	-7.0687903E-01	3.8330964E 00	-2.5710703E-01	-3.2586023E-01	2.6988180E 00	
III	27	1.7577056E-03	2.8339747E-04	3.9620970E-04	-1.1928093E-03	1.1323065E-03	-3.8325585E-04	
	28	-1.7199886E-04	2.5405724E-02	-1.4097031E-04	-8.4594524E-04	1.0420042E-03	7.3792368E-03	
	29	-6.0263882E-02	-1.1798609E-01	4.4274451E-03	3.4380887E-02	-4.3196892E-02	-1.6411811E-02	
	30		-1.0068053E-01	1.0509565E-03	5.7696413E-02	-5.1688339E-02		
	31		-2.8248769E-02	-1.4250337E-01	2.2878611E-03	-1.1179516E-02		
	32		-2.3730302E-02	3.5673083E-03	8.4789476E-03	-1.0958873E-02		
	33		3.3189850E-01	-2.9969407E-02	1.0507941E-02	1.2241141E-01		
	34		2.8828480E-01	-1.0279219E-02	-1.6039630E-01	1.4685266E-01		
	35			3.8839197E-01				
	36							

Hormonic		4		5		6	
GEOGRAPHICAL VARIATION	K \ S	7	8	9	10	11	12
I	0	2.0321863E-02	4.4910491E-03	1.0973362E-02	2.5578273E-02	-4.8214887E-03	1.2555835E-03
	1	4.4199712E-02	-8.7826320E-02	2.0691925E-02	-3.2183440E-03	4.3740110E-03	1.8809402E-02
	2	-3.1068542E-02	9.8289336E-04	-1.6551957E-02	-1.2071578E-01	4.1033049E-03	-3.7992496E-03
	3	-6.2312560E-02	1.0633776E-01	-2.7050457E-02	-2.1341972E-03		-2.6559583E-02
	4				9.8221246E-02		

I - Moin lotitudinol voriotion. Mixed latitudinol ond longitudinal voriotion: II - First order in longitude, III - Second order in longitude.

Nototion: For each entry the number given by the first eight digits ond sign is multiplied by the power of ten defined by the lost two digits and sign.

COEFFICIENTS D_{SK} DEFINING THE FUNCTION $\Gamma(\lambda,\theta,t)$ FOR MONTHLY MEDIAN F2-M 3000
DECEMBER 1958

TABLE 3. GEOGRAPHIC FUNCTIONS $G_k(\lambda, \theta)$

MAIN LATITUDINAL VARIATION		MIXED LATITUDINAL AND LONGITUDINAL VARIATION			
		FIRST ORDER IN LONGITUDE		SECOND ORDER IN LONGITUDE	
k	$G_k(\lambda, \theta)$	k	$G_k(\lambda, \theta)$	k	$G_k(\lambda, \theta)$
0	1	$k_o + 1$	$\cos \lambda \cos \theta$	$k_1 + 1$	$\cos^2 \lambda \cos 2\theta$
1	$\sin \lambda$	$k_o + 2$	$\cos \lambda \sin \theta$	$k_1 + 2$	$\cos^2 \lambda \sin 2\theta$
2	$\sin^2 \lambda$	$k_o + 3$	$\sin \lambda \cos \lambda \cos \theta$	$k_1 + 3$	$\sin \lambda \cos^2 \lambda \cos 2\theta$
		$k_o + 4$	$\sin \lambda \cos \lambda \sin \theta$	$k_1 + 4$	$\sin \lambda \cos^2 \lambda \sin 2\theta$
k_o	$\sin^{q_o} \lambda$				
			$\sin^{q_1} \lambda \cos \lambda \cos \theta$	$K - 1$	$\sin^{q_2} \lambda \cos^2 \lambda \cos 2\theta$
			$\sin^{q_1} \lambda \cos \lambda \sin \theta$	K	$\sin^{q_2} \lambda \cos^2 \lambda \sin 2\theta$

667310 O - 62 - 4

DECEMBER, 1958

UT = 00

LONGITUDE

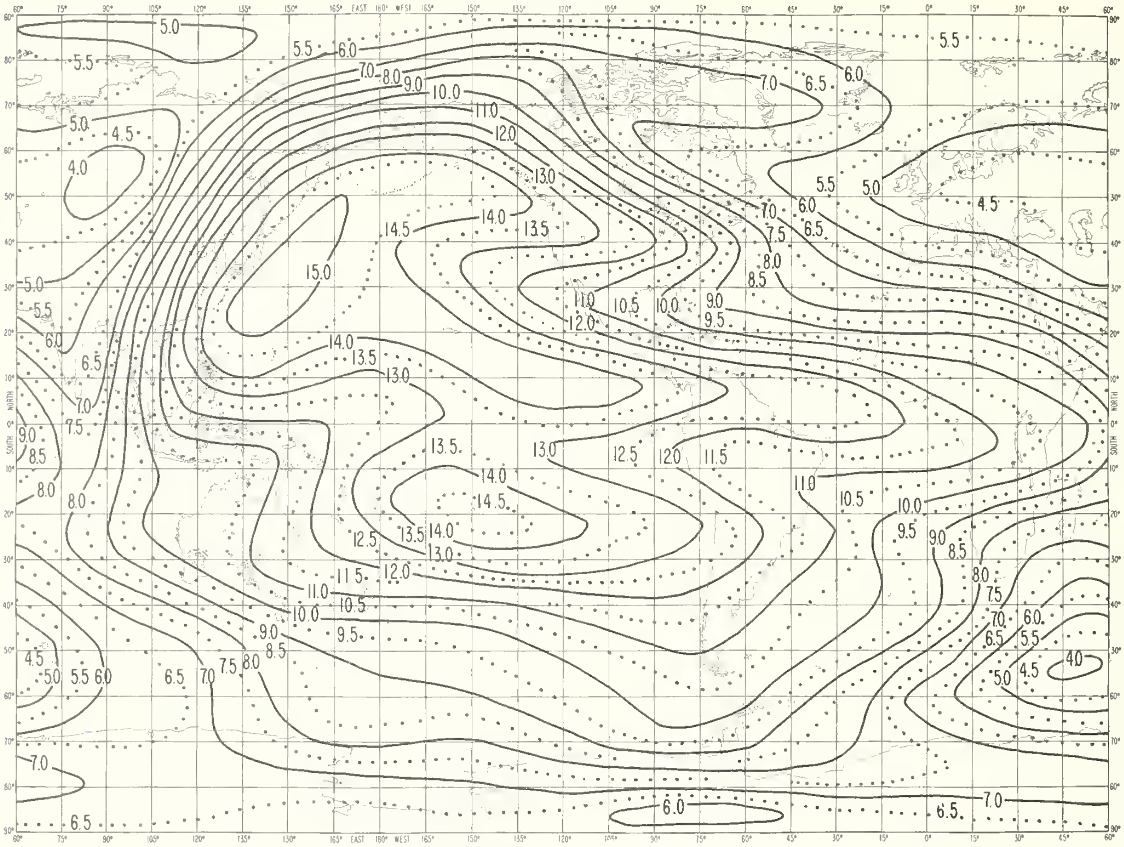


FIG. 1A. MEDIAN F2-ZERO-MUF (Mc/s)

GEOGRAPHIC LATITUDE, DEGREES

LONGITUDE

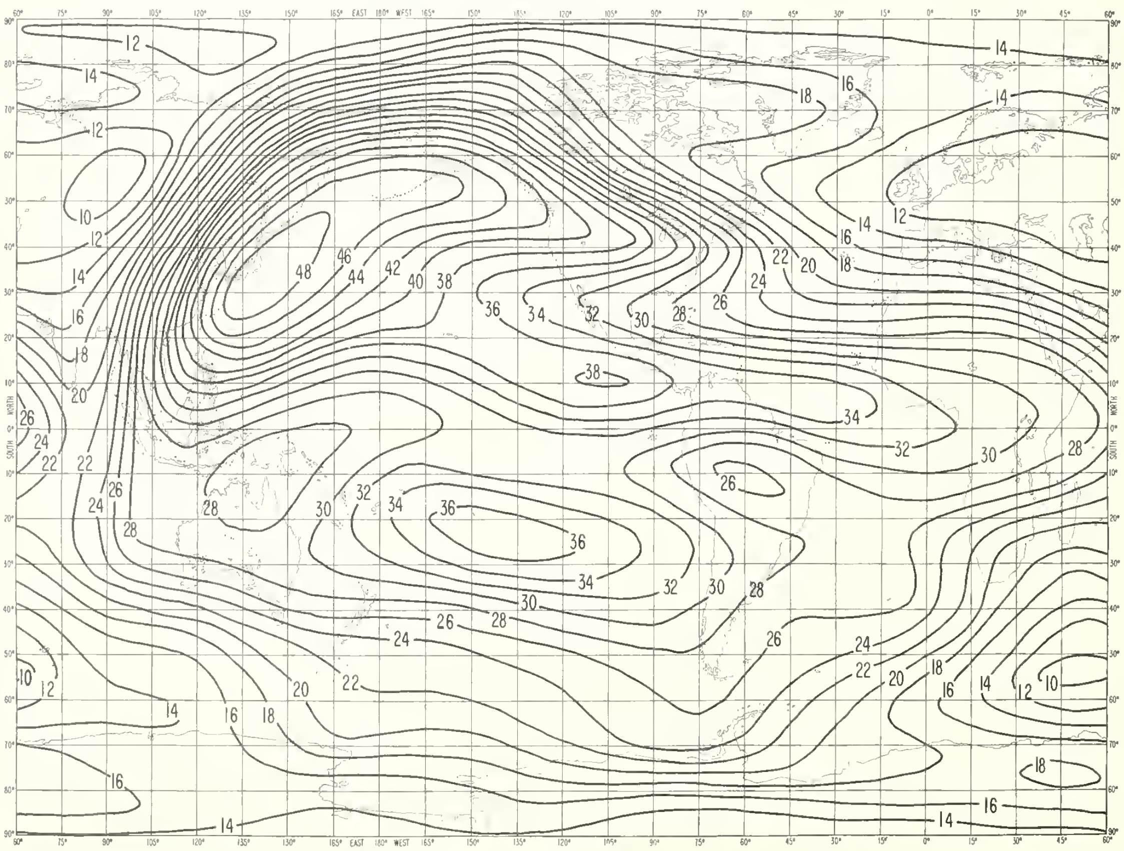


FIG. 1B. MEDIAN F2-4000-MUF (Mc/s)

DECEMBER, 1958

UT = 02

LONGITUDE

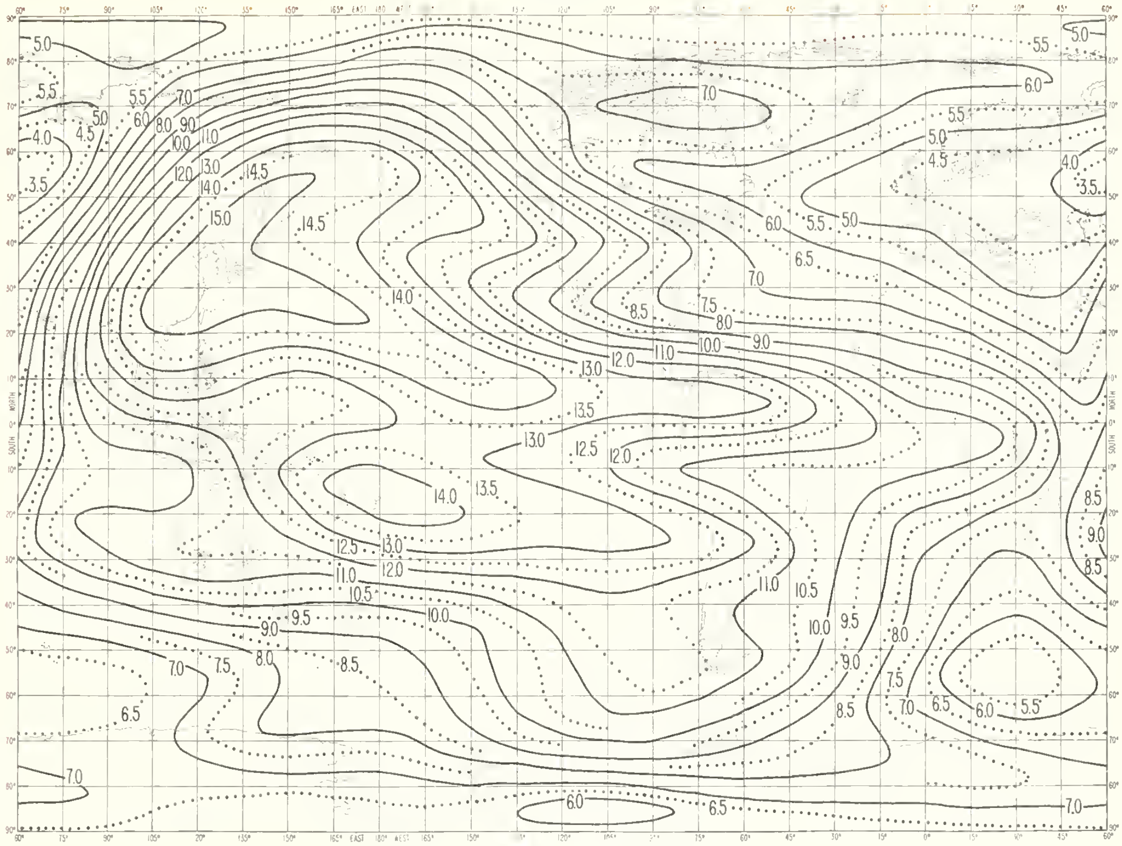


FIG. 2A. MEDIAN F2-ZERO-MUF (Mc/s)

LONGITUDE

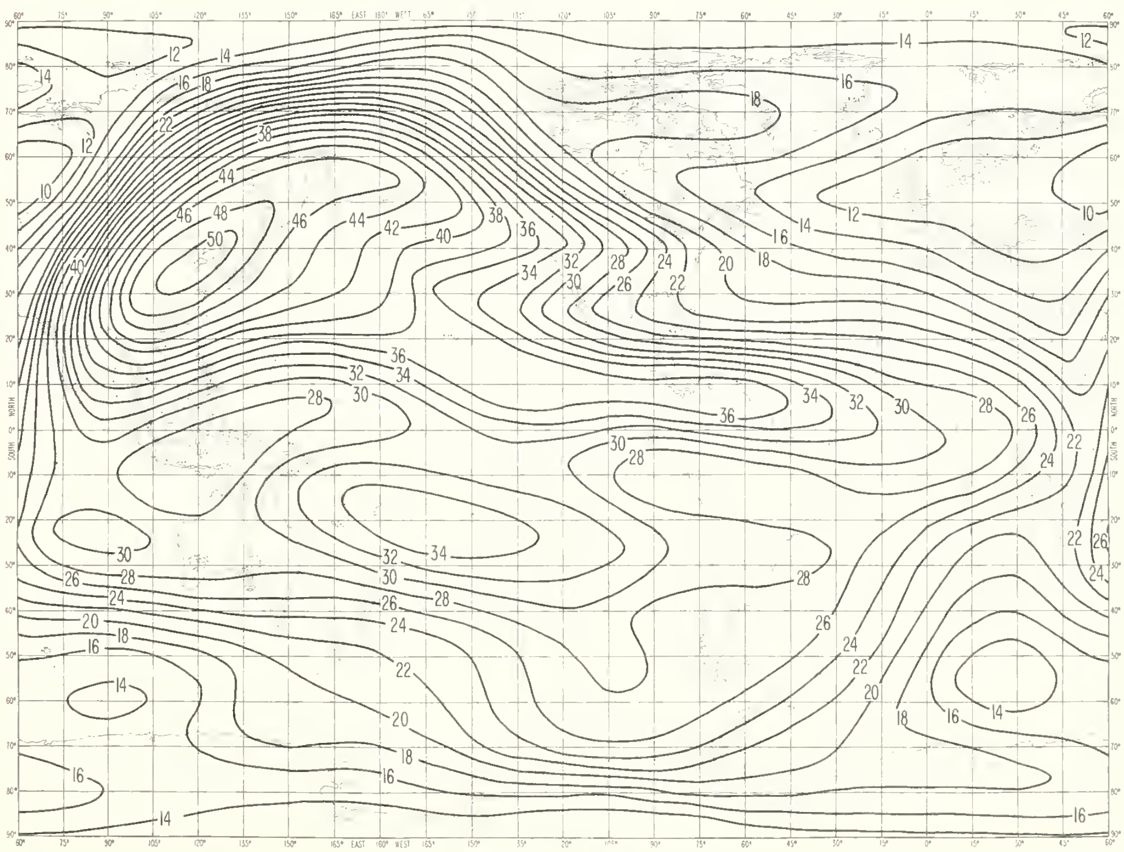


FIG. 2B. MEDIAN F2-4000-MUF (Mc/s)

GEOGRAPHIC LATITUDE, DEGREES

DECEMBER, 1958

UT = 04

LONGITUDE

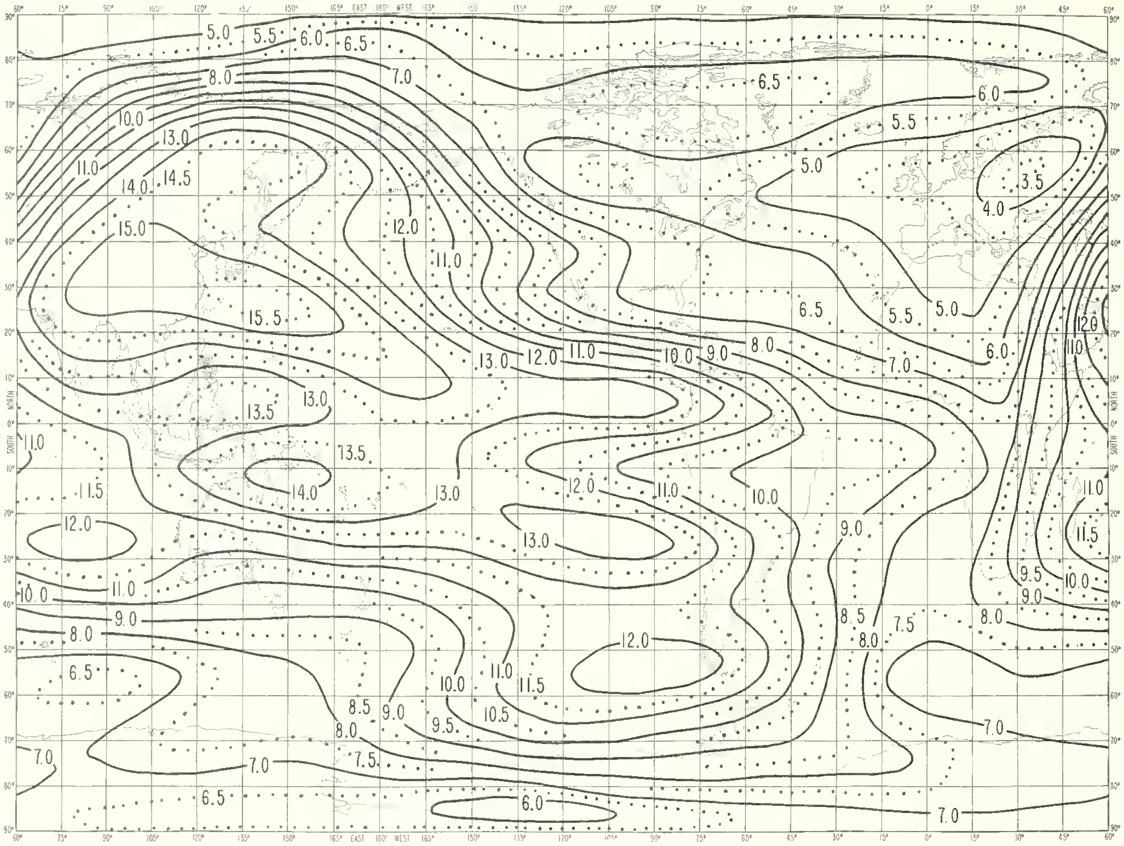


FIG. 3A. MEDIAN F2-ZERO-MUF (Mc/s)

LONGITUDE

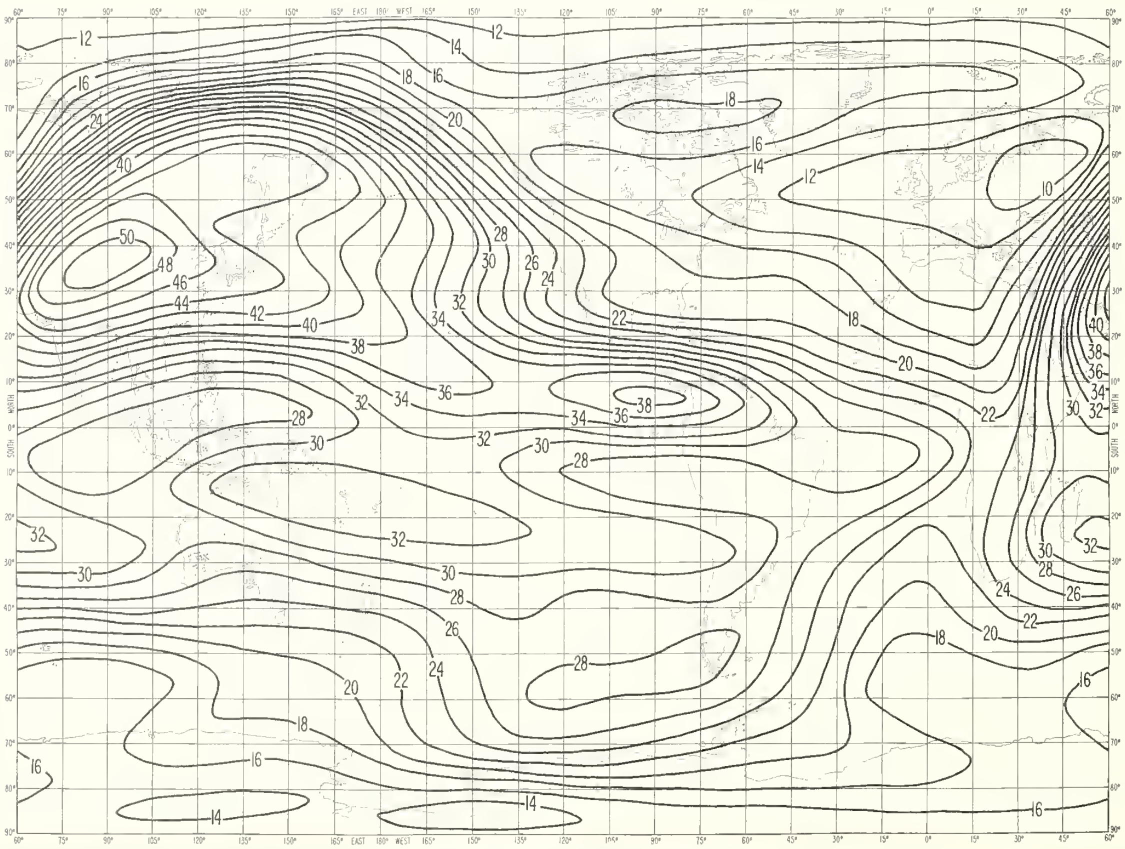


FIG. 3B. MEDIAN F2-4000-MUF (Mc/s)

DECEMBER, 1958

UT = 06

LONGITUDE

GEOGRAPHIC LATITUDE, DEGREES

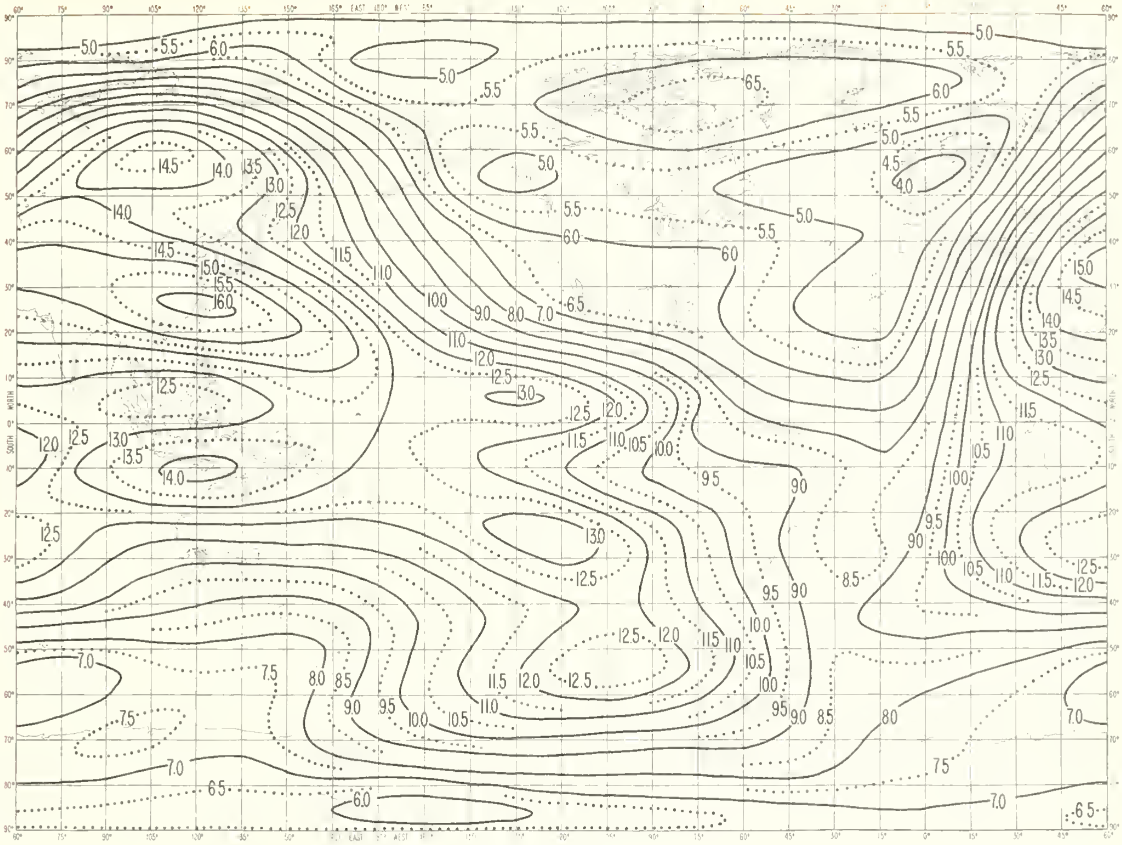


FIG. 4A. MEDIAN F2-ZERO-MUF (Mc/s)

LONGITUDE

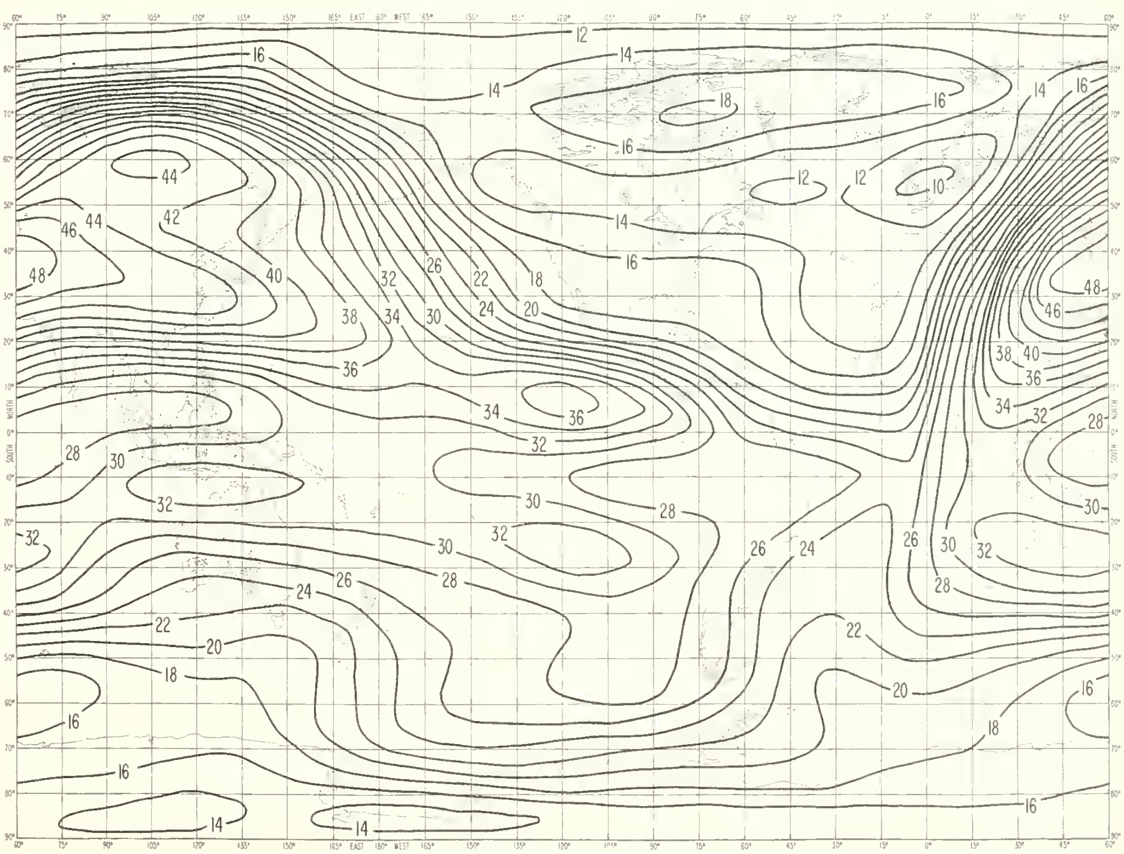


FIG. 4B. MEDIAN F2-4000-MUF (Mc/s)

DECEMBER, 1958

UT = 08

LONGITUDE

GEOGRAPHIC LATITUDE, DEGREES

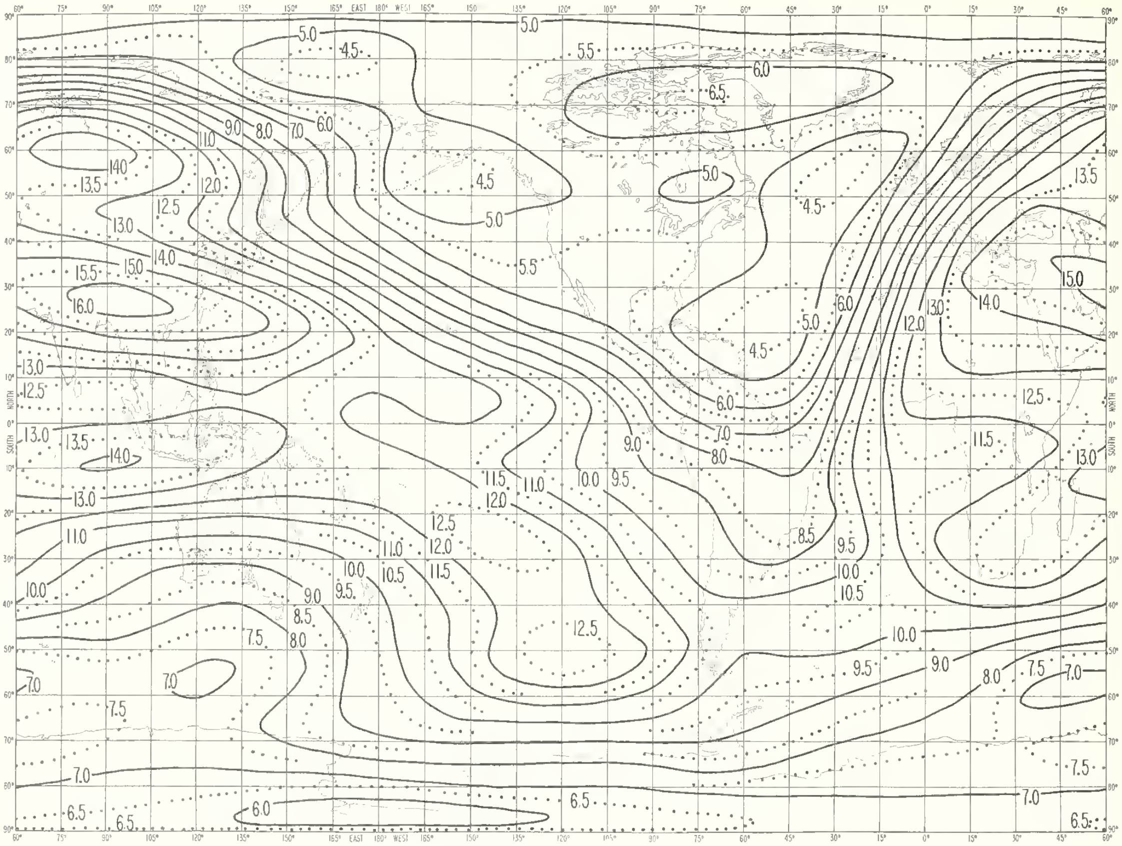


FIG. 5A. MEDIAN F2-ZERO-MUF (Mc/s)

LONGITUDE

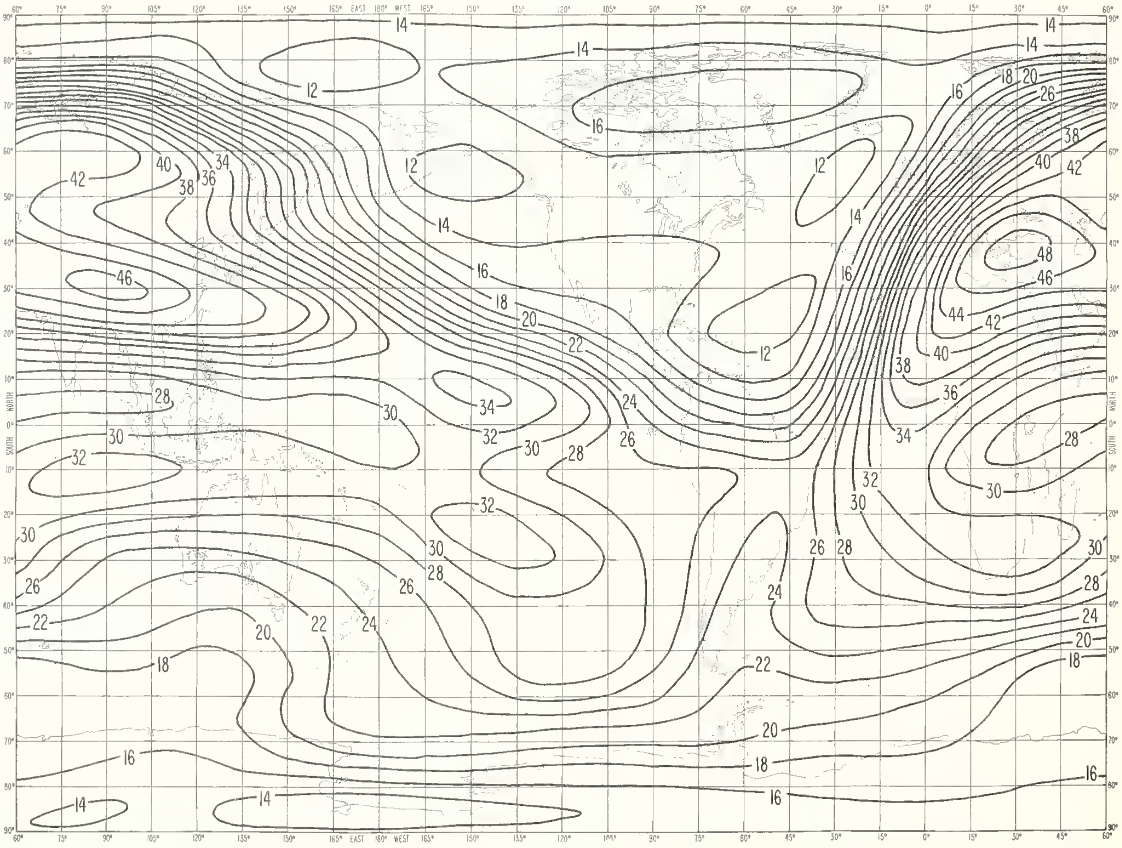


FIG. 5B. MEDIAN F2-4000-MUF (Mc/s)

DECEMBER, 1958

UT = 10

LONGITUDE

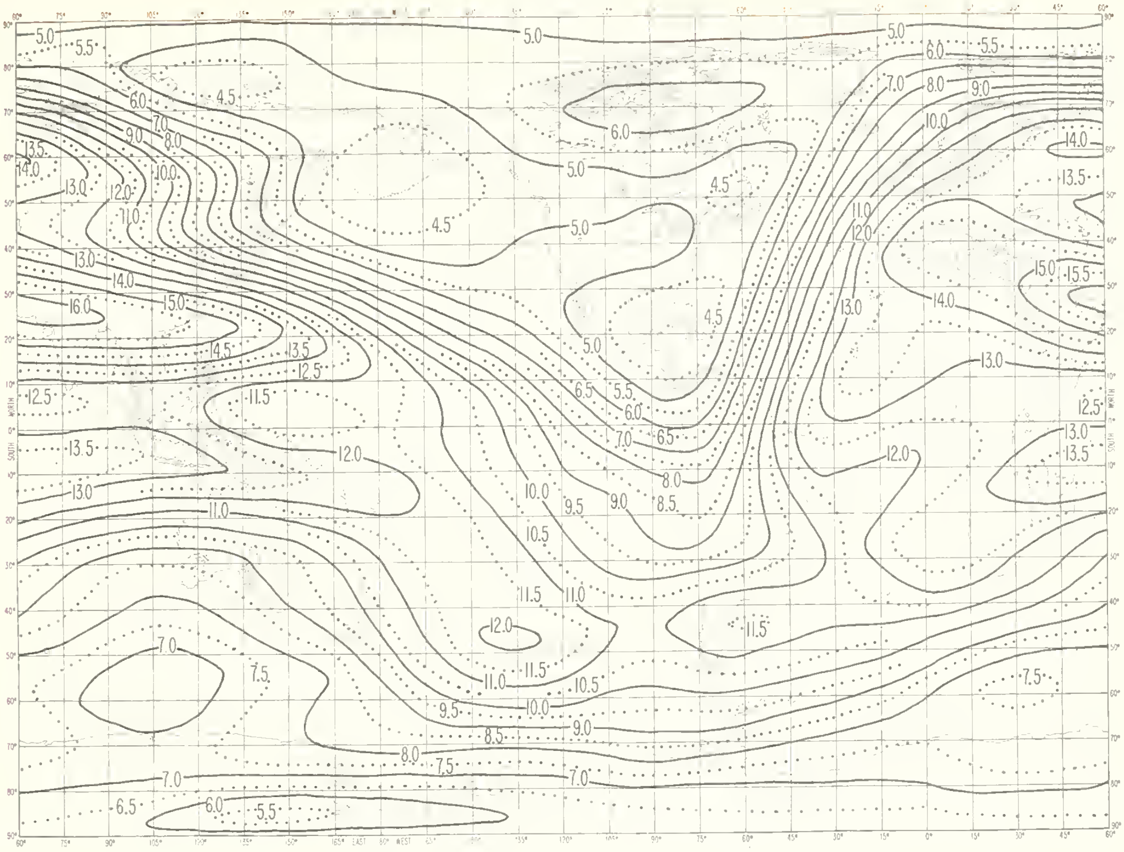


FIG. 6A. MEDIAN F2-ZERO-MUF (Mc/s)

GEOGRAPHIC LATITUDE, DEGREES

LONGITUDE

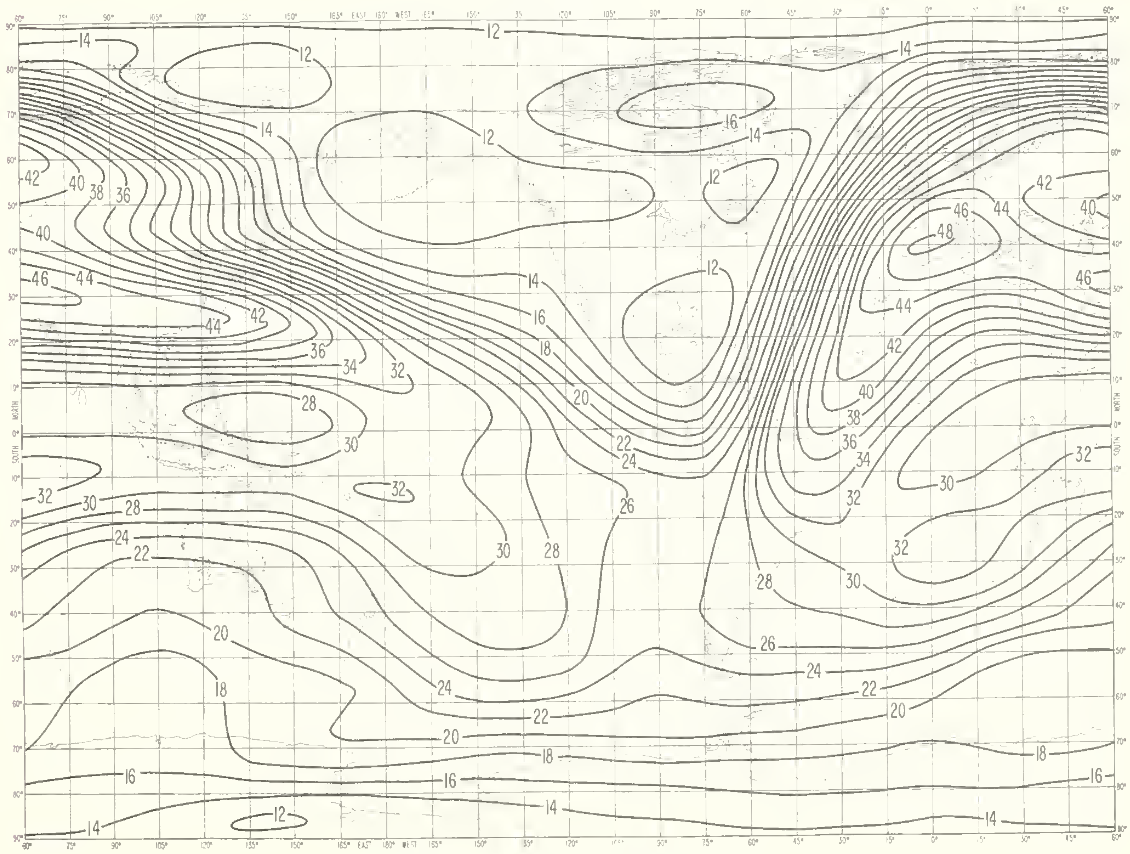


FIG. 6B. MEDIAN F2-4000-MUF (Mc/s)

DECEMBER, 1958

UT = 12

LONGITUDE

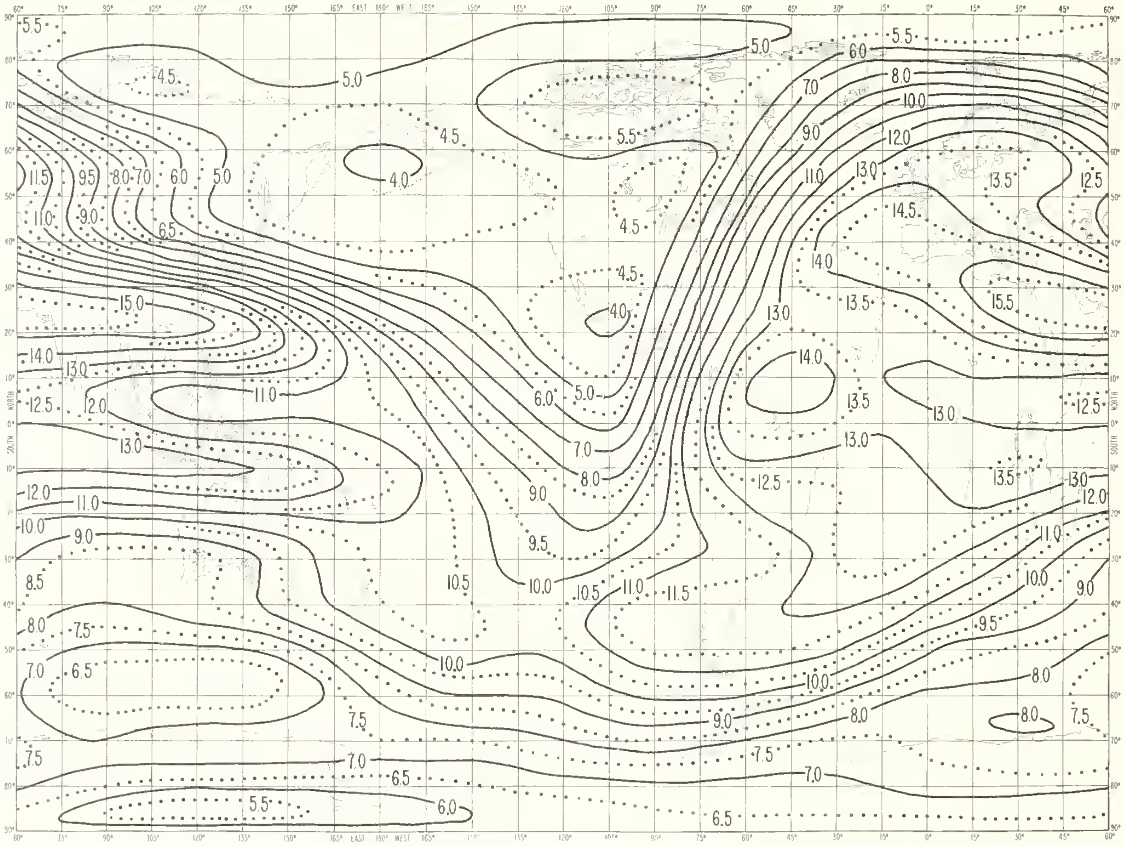


FIG. 7A. MEDIAN F2-ZERO-MUF (Mc/s)

GEOGRAPHIC LATITUDE, DEGREES

LONGITUDE

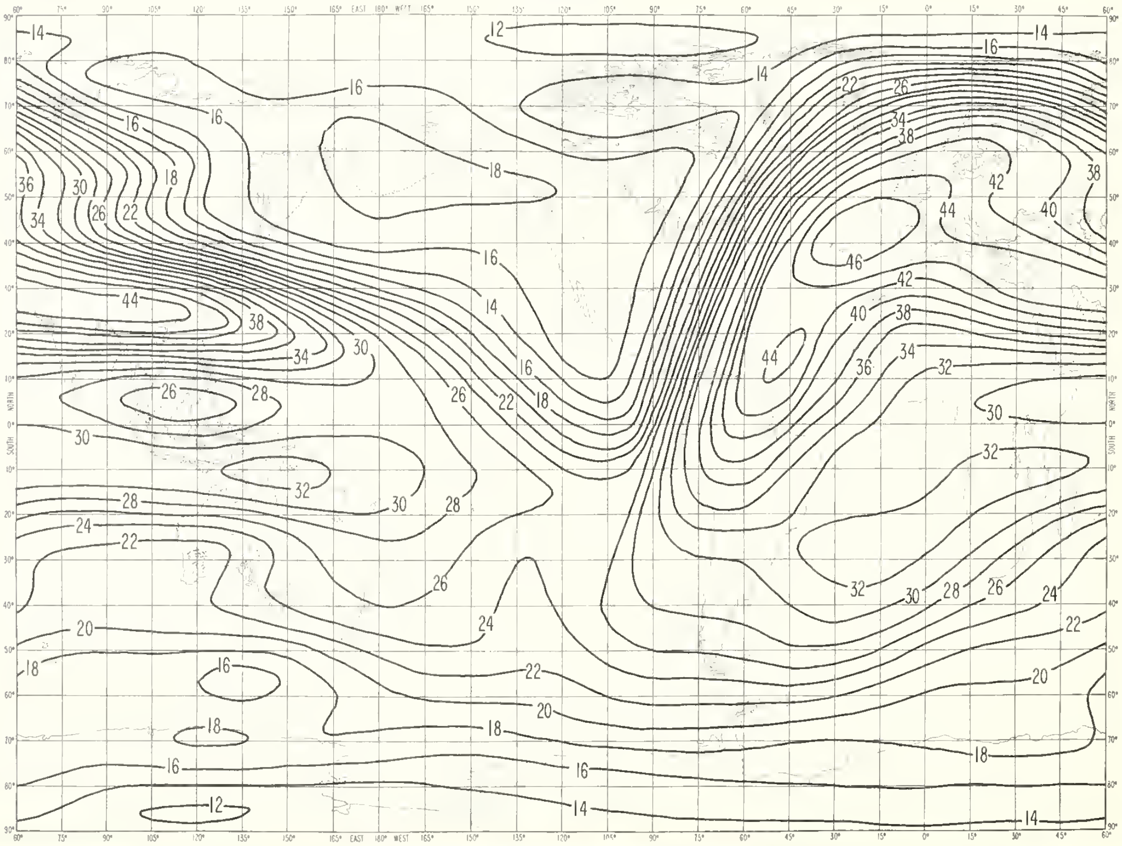


FIG. 7B. MEDIAN F2-4000-MUF (Mc/s)

DECEMBER, 1958

UT = 14

LONGITUDE

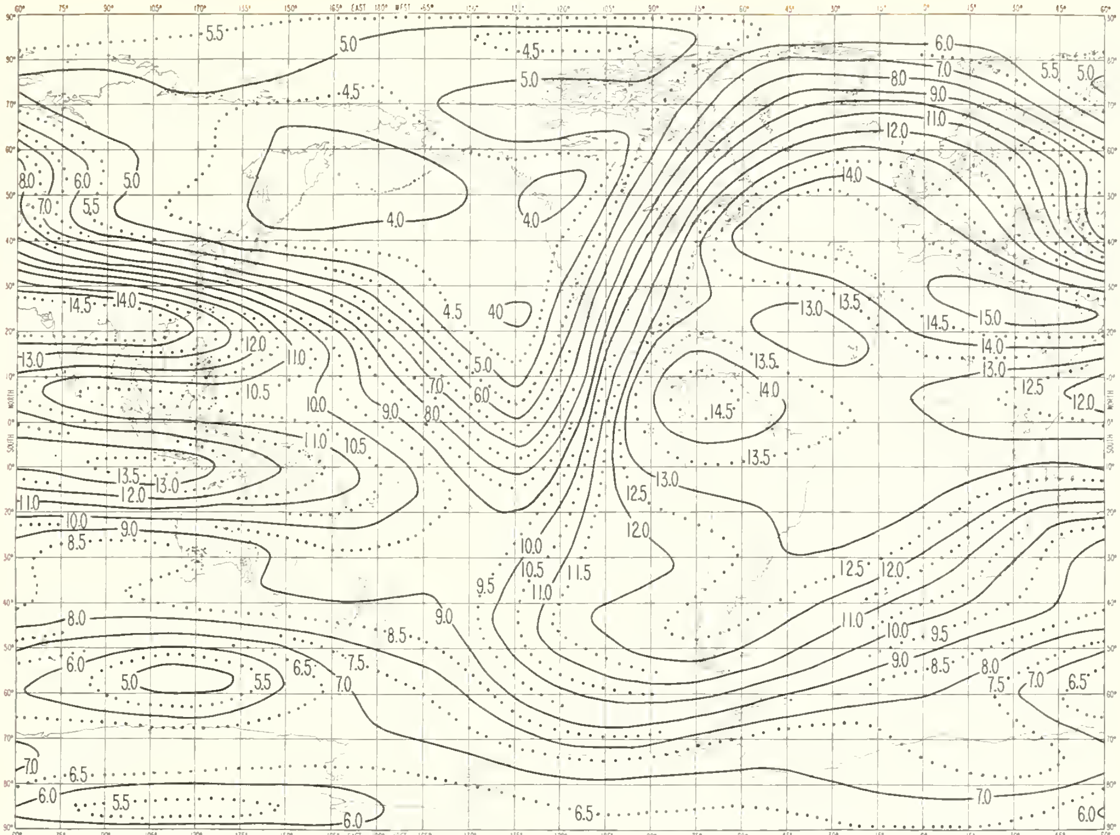


FIG. 8A. MEDIAN F2-ZERO-MUF (Mc/s)

GEOGRAPHIC LATITUDE, DEGREES

LONGITUDE

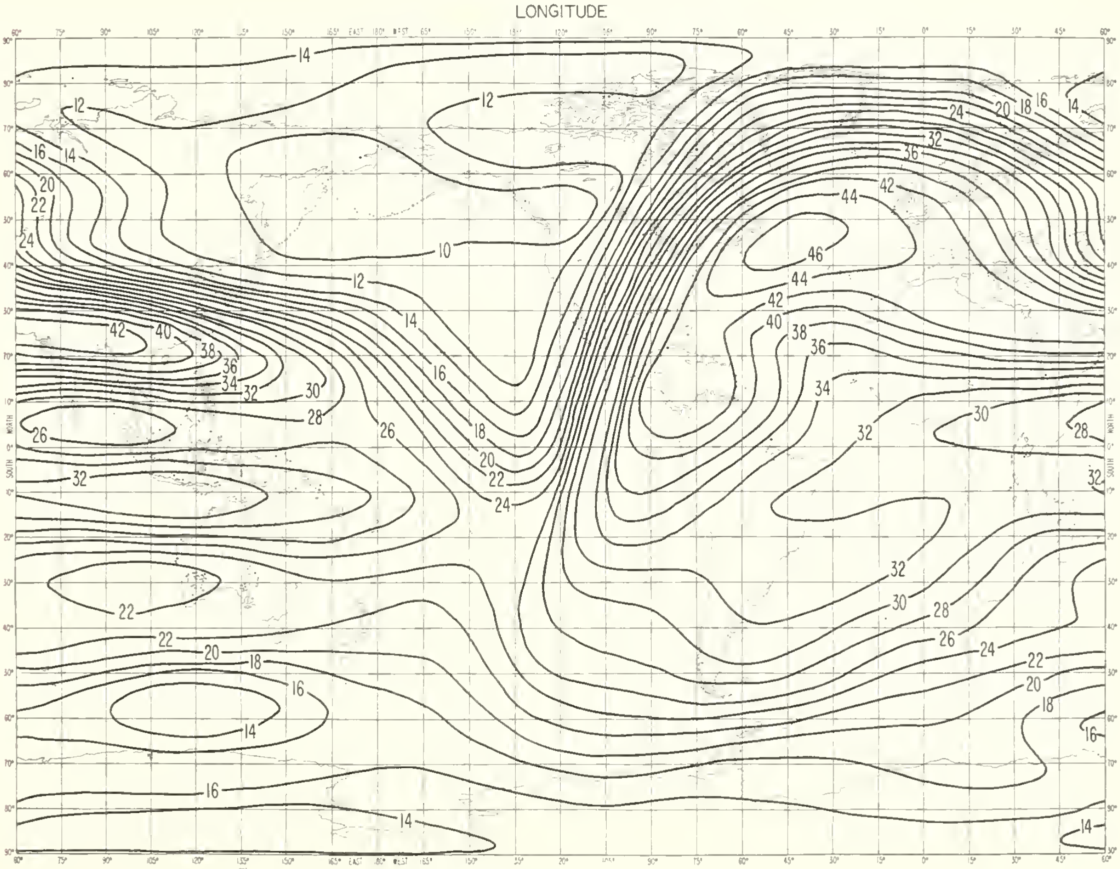


FIG. 8B. MEDIAN F2-4000-MUF (Mc/s)

DECEMBER, 1958

UT = 16

LONGITUDE

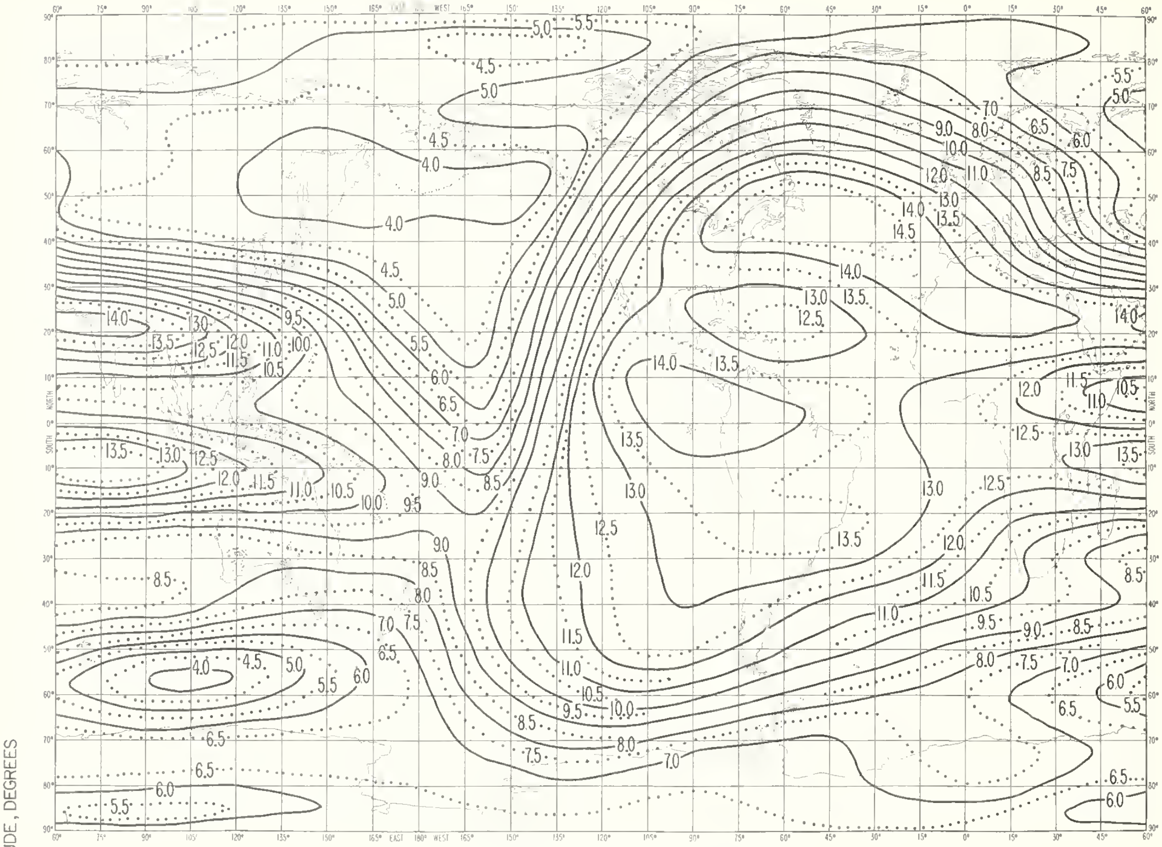


FIG. 9A. MEDIAN F2-ZERO-MUF (Mc/s)

LONGITUDE

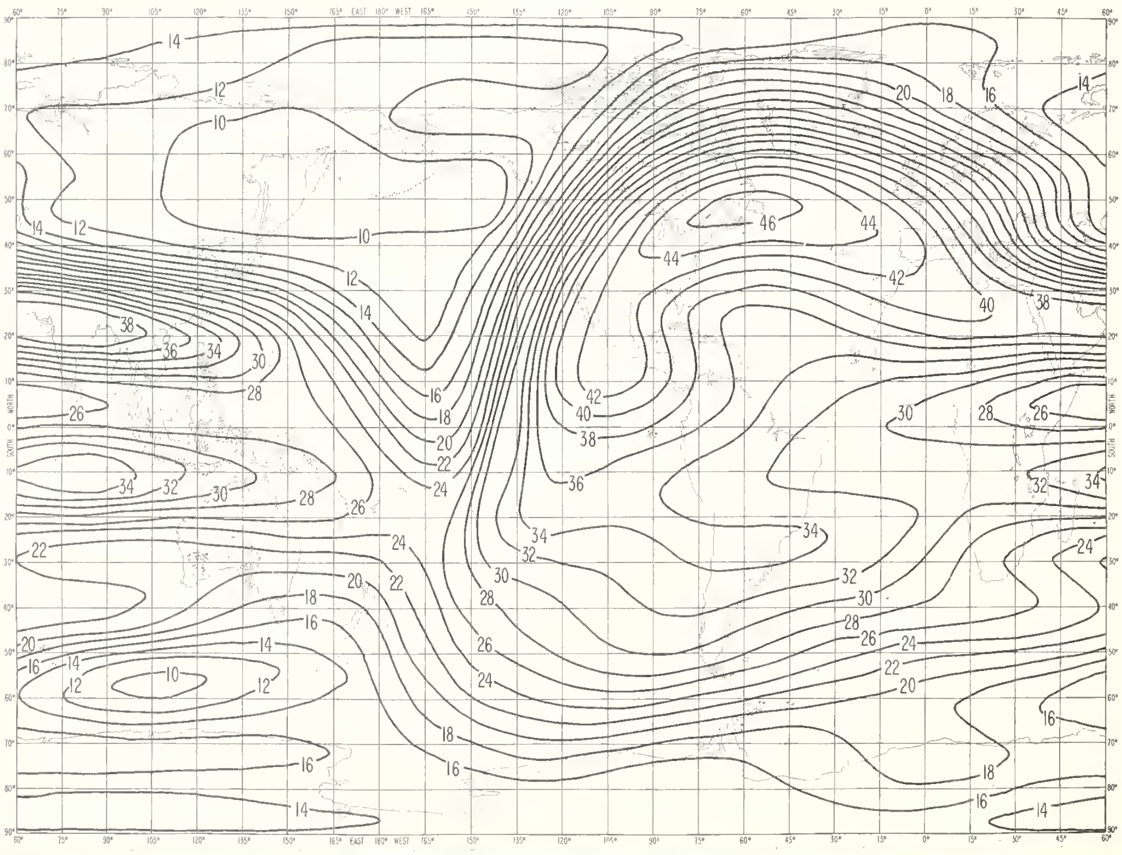


FIG. 9B. MEDIAN F2-4000-MUF (Mc/s)

DECEMBER, 1958

UT = 18

LONGITUDE

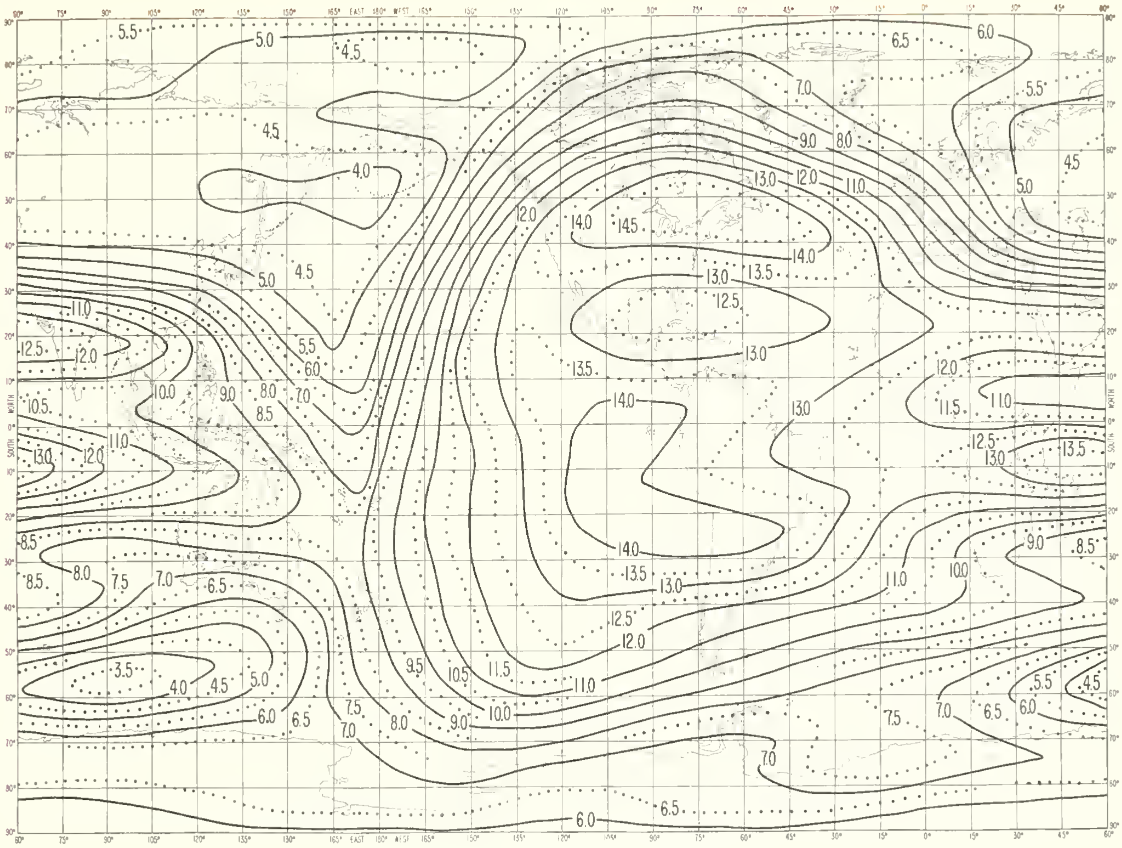


FIG. 10A MEDIAN F2-ZERO-MUF (Mc/s)

GEOGRAPHIC LATITUDE, DEGREES

LONGITUDE

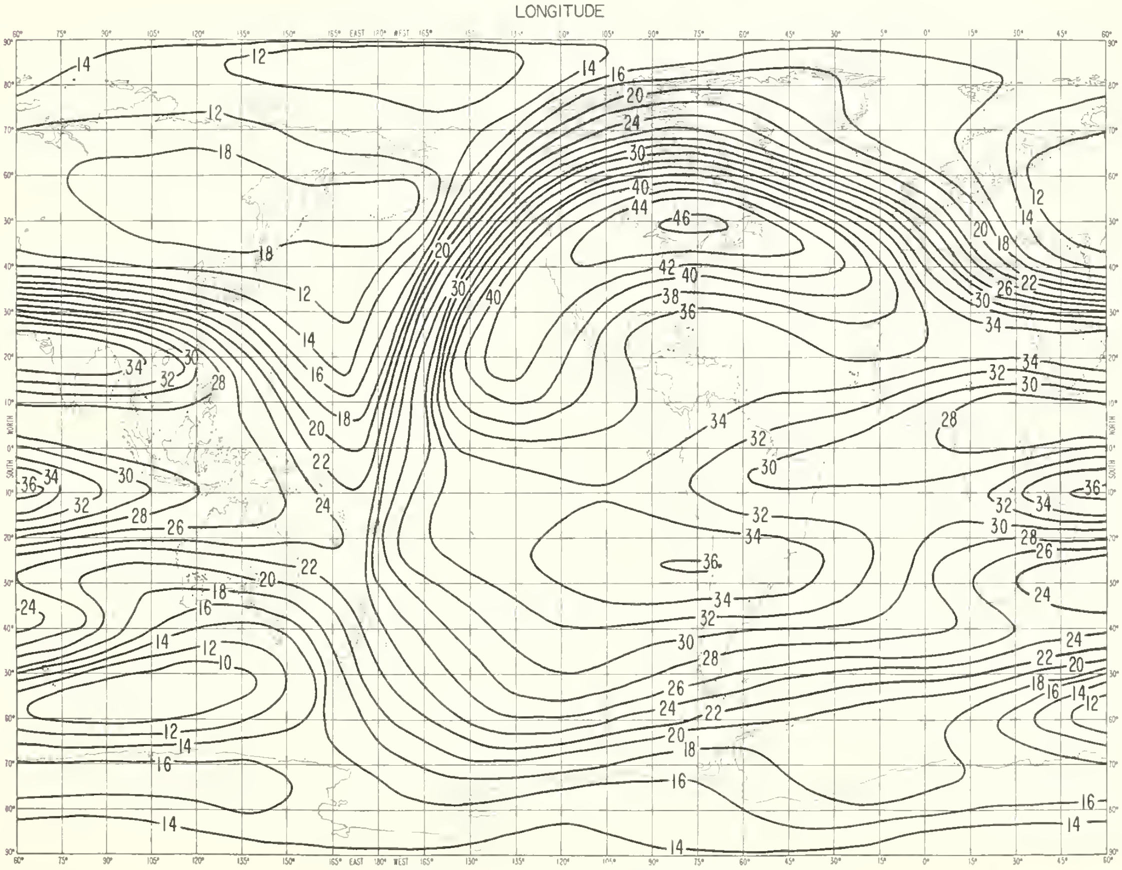


FIG. 10B. MEDIAN F2-4000-MUF (Mc/s)

DECEMBER, 1958

UT = 20

LONGITUDE

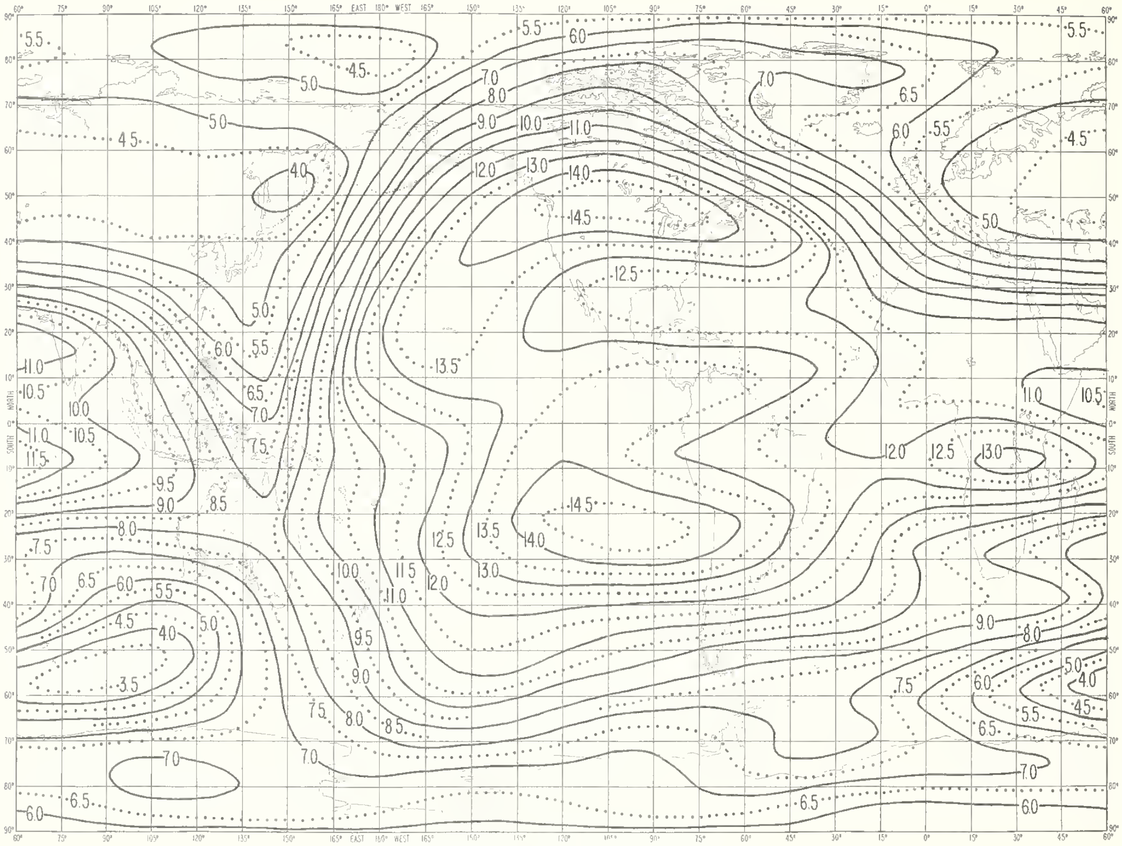
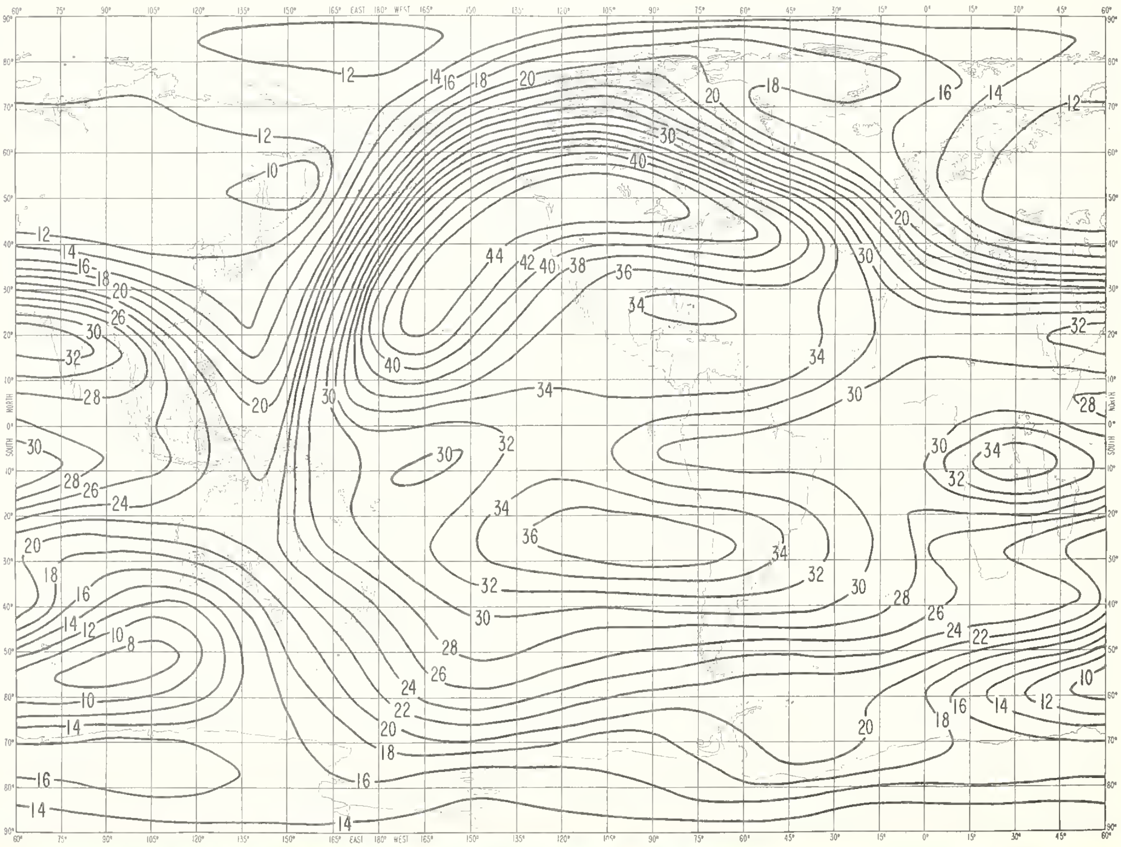


FIG. 11A. MEDIAN F2-ZERO-MUF (Mc/s)

LONGITUDE



GEOGRAPHIC LATITUDE, DEGREES

FIG. 11B. MEDIAN F2-4000-MUF (Mc/s)

DECEMBER, 1958

UT = 22

LONGITUDE

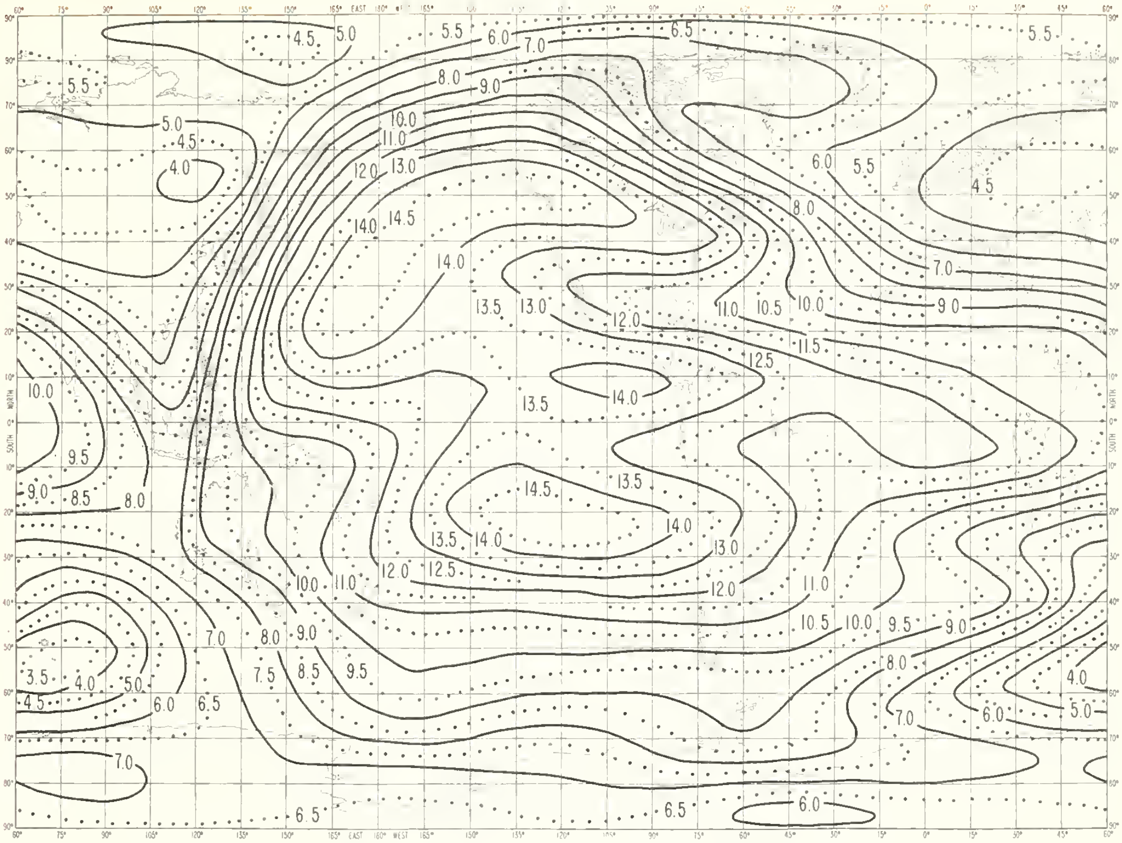


FIG. 12A. MEDIAN F2-ZERO-MUF (Mc/s)

GEOGRAPHIC LATITUDE, DEGREES

LONGITUDE

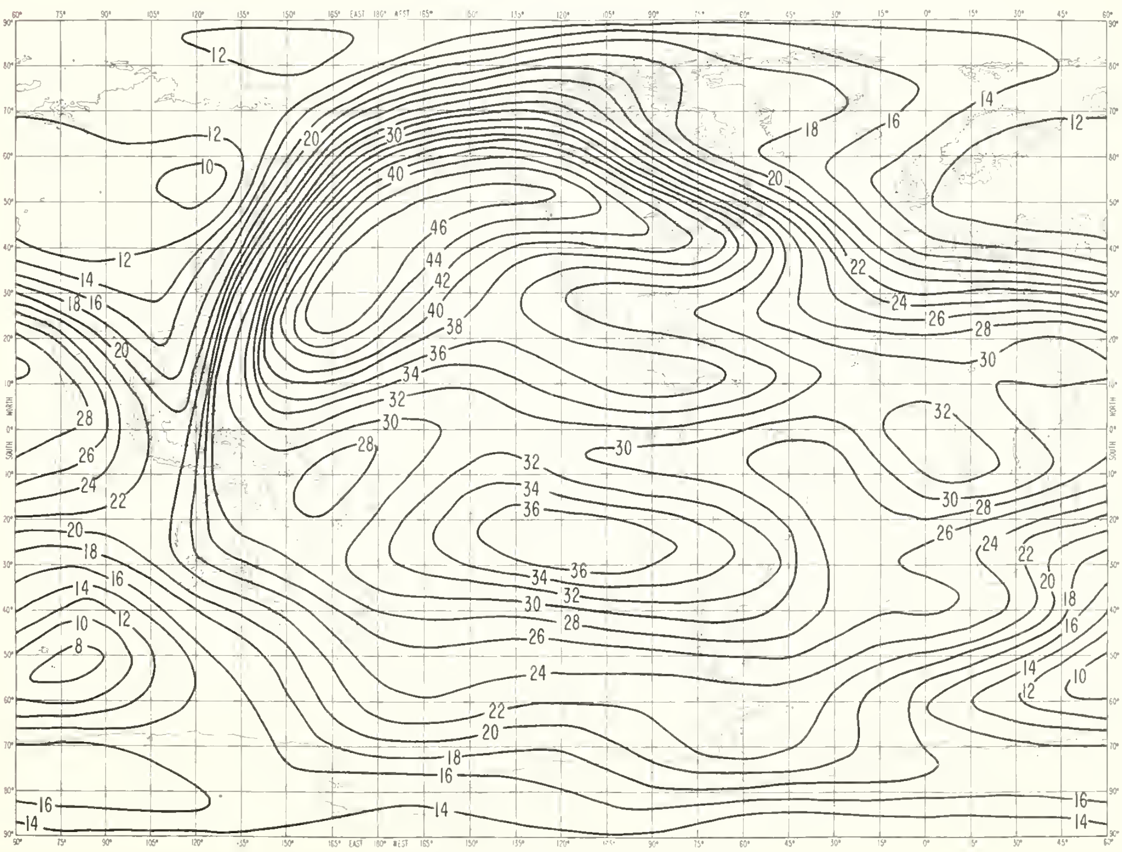


FIG. 12B. MEDIAN F2-4000-MUF (Mc/s)

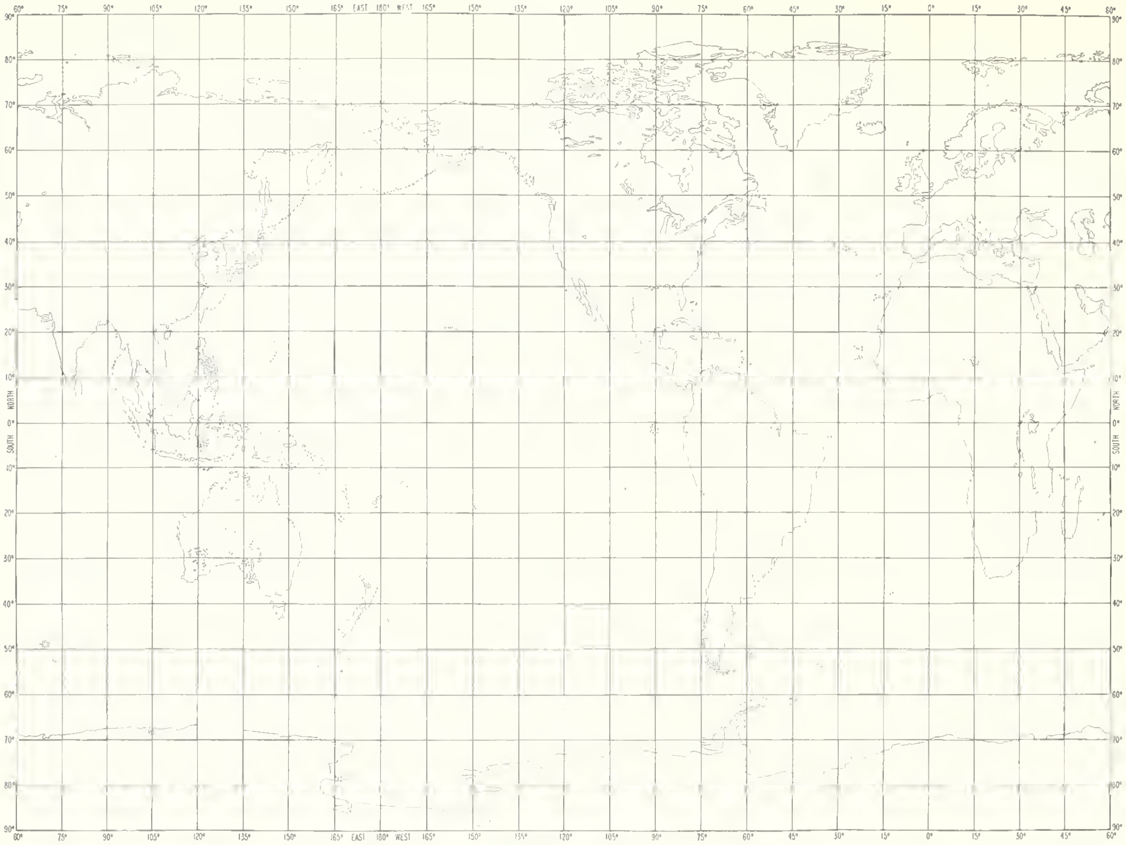


FIG. 13. WORLD MAP, MODIFIED CYLINDRICAL PROJECTION.

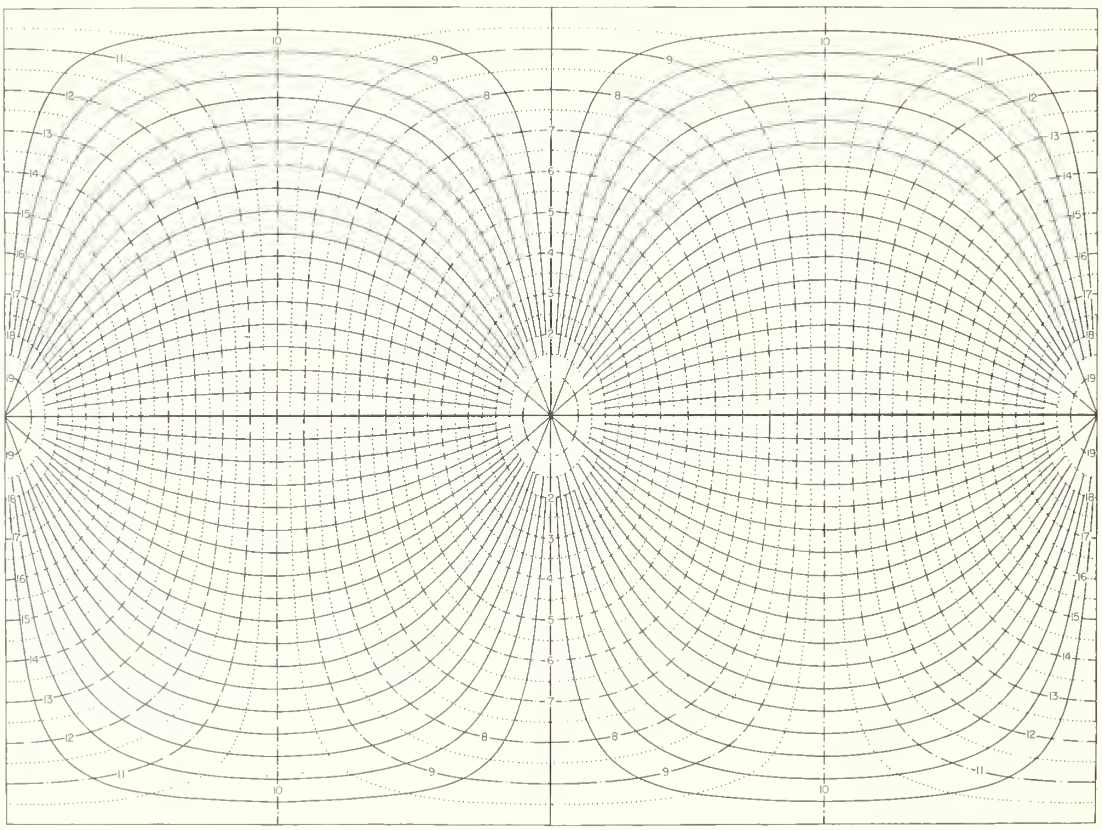


FIG. 14. GREAT CIRCLE CHART CENTERED ON EQUATOR FOR MODIFIED CYLINDRICAL PROJECTION WORLD MAP.

(SOLID LINES REPRESENT GREAT CIRCLES. NUMBERED DOT-DASH LINES INDICATE DISTANCE IN THOUSANDS OF KILOMETERS.)

NORTH POLAR AREA
DECEMBER, 1958
UT = 00

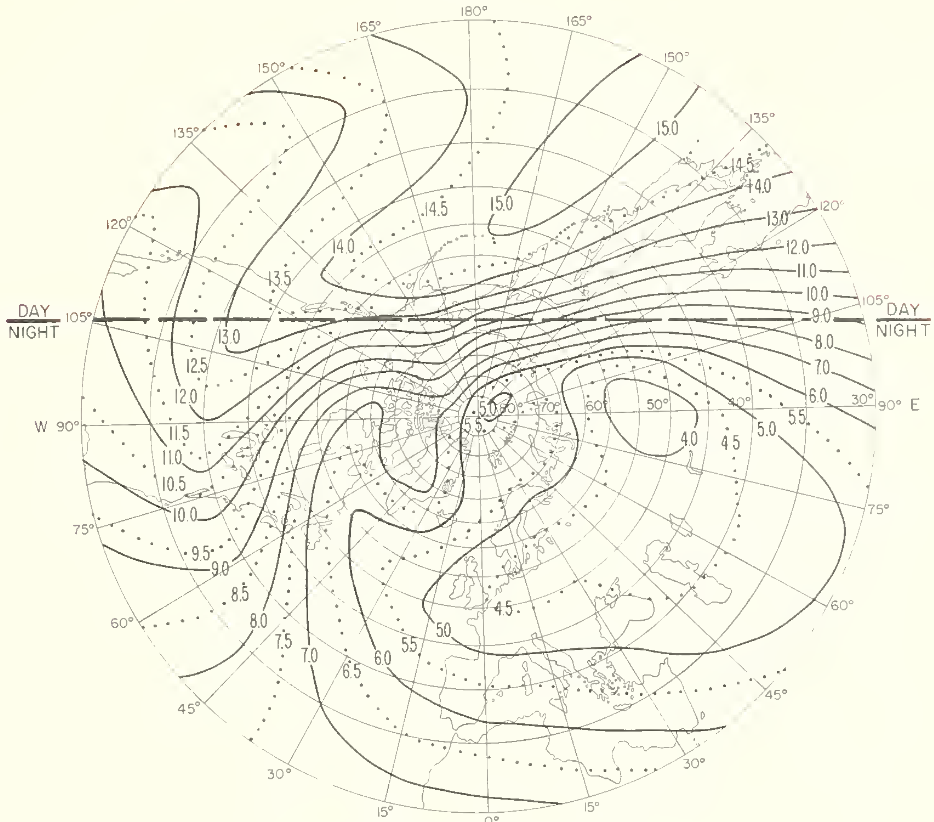


FIG. 15A. MEDIAN F2-ZERO-MUF (MC/S)

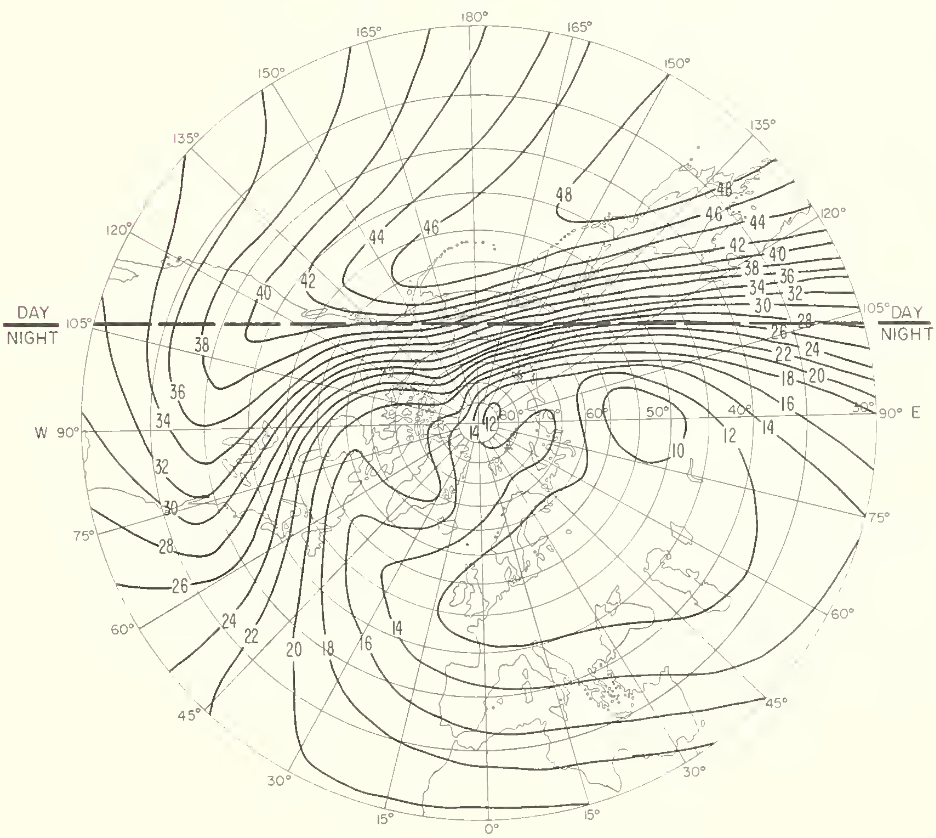


FIG. 15B. MEDIAN F2-4000-MUF (MC/S)

SOUTH POLAR AREA
DECEMBER, 1958
UT = 00

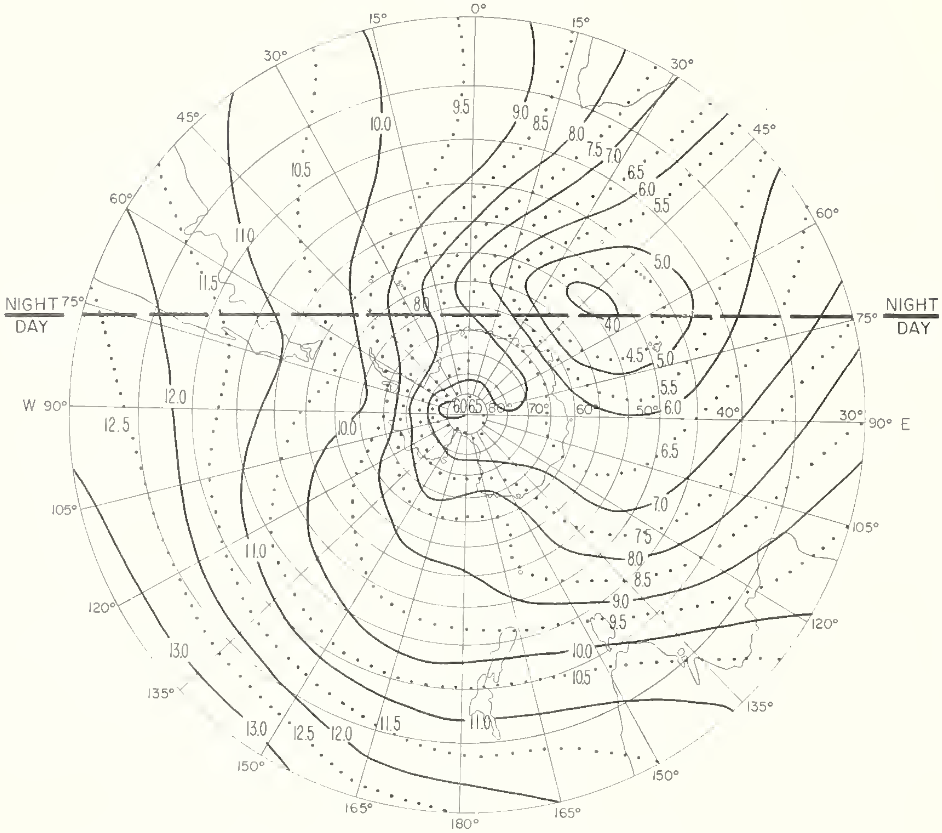


FIG. 16A. MEDIAN F2-ZERO-MUF (Mc/s)

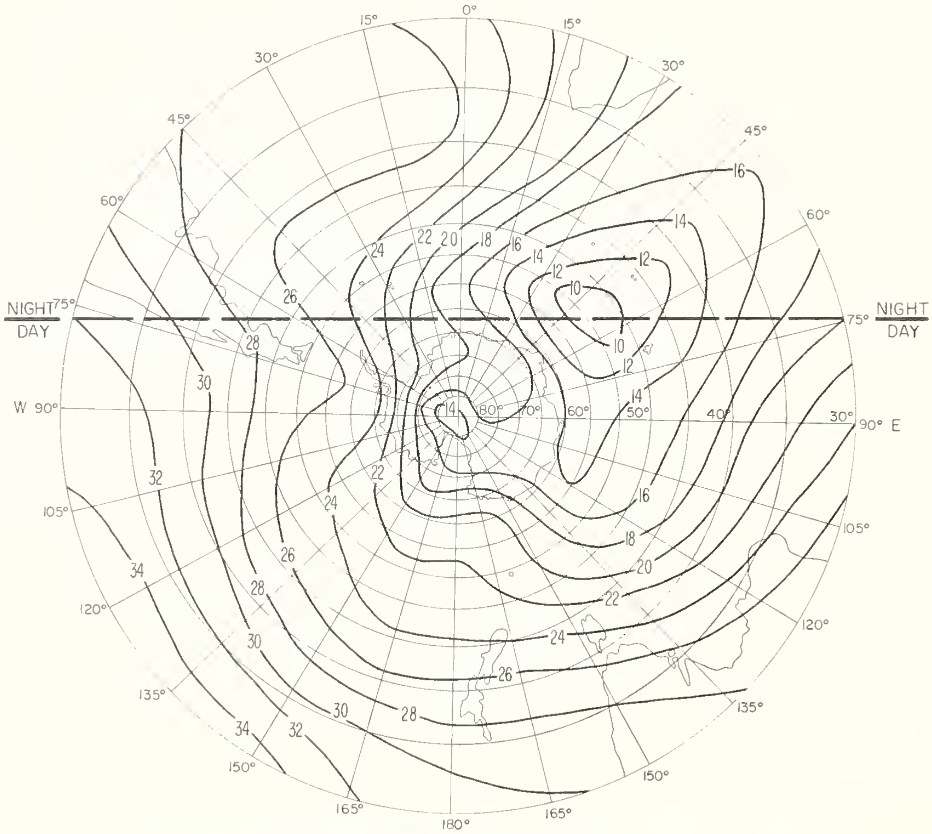


FIG 16B. MEDIAN F2-4000-MUF (Mc/s)

NORTH POLAR AREA
DECEMBER, 1958
UT = 12

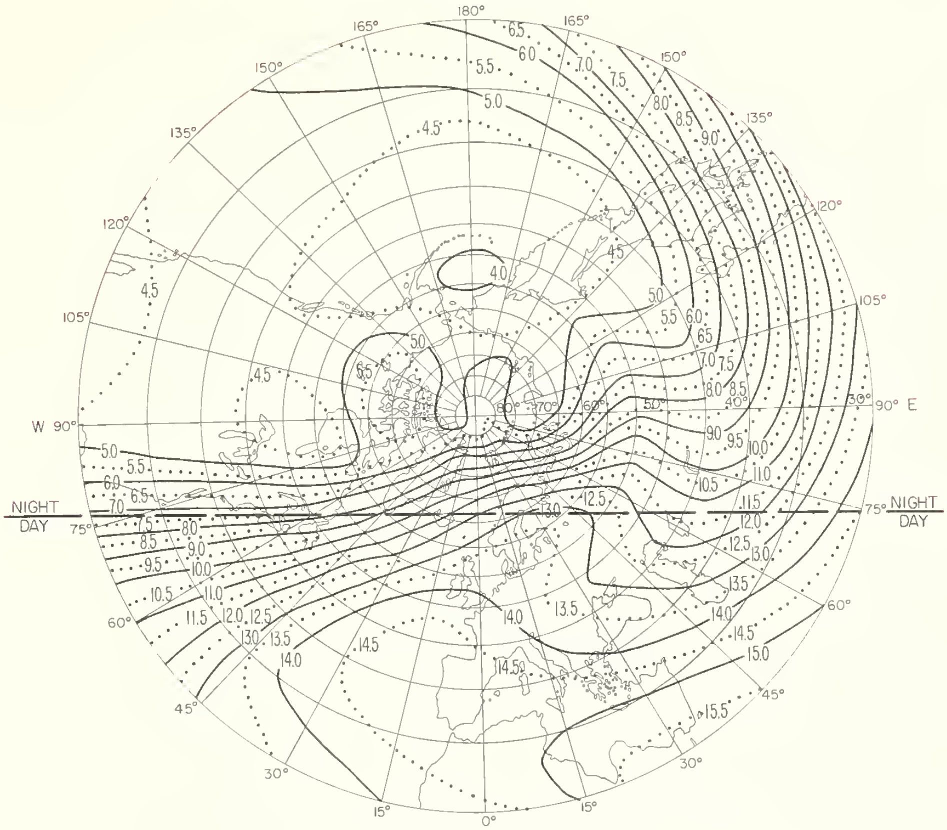


FIG. 17A. MEDIAN F2-ZERO-MUF (Mc/s)

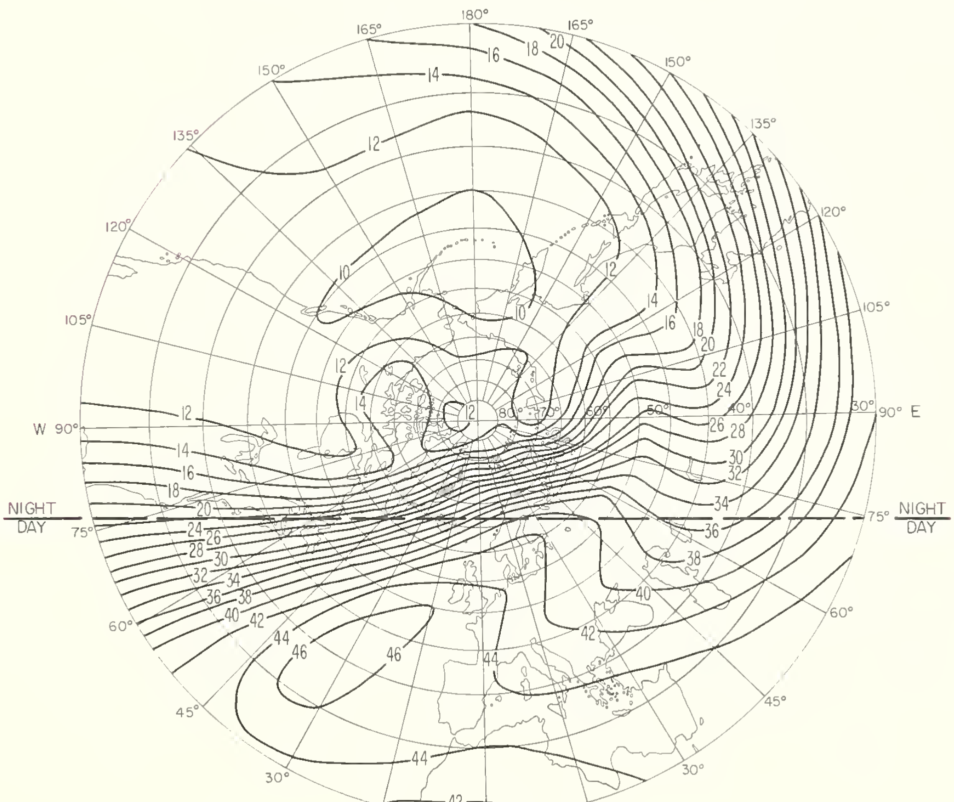


FIG. 17B. MEDIAN F2-4000-MUF (Mc/s)

SOUTH POLAR AREA
DECEMBER, 1958
UT = 12

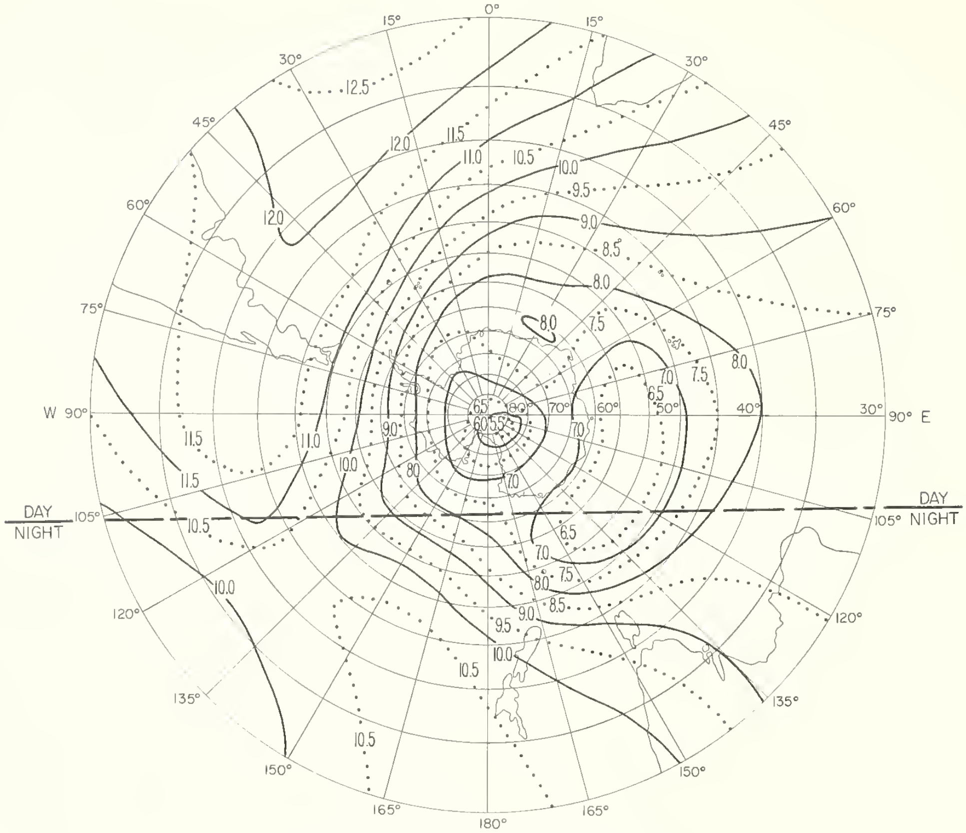


FIG. 18A. MEDIAN F2-ZERO-MUF (Mc/s)

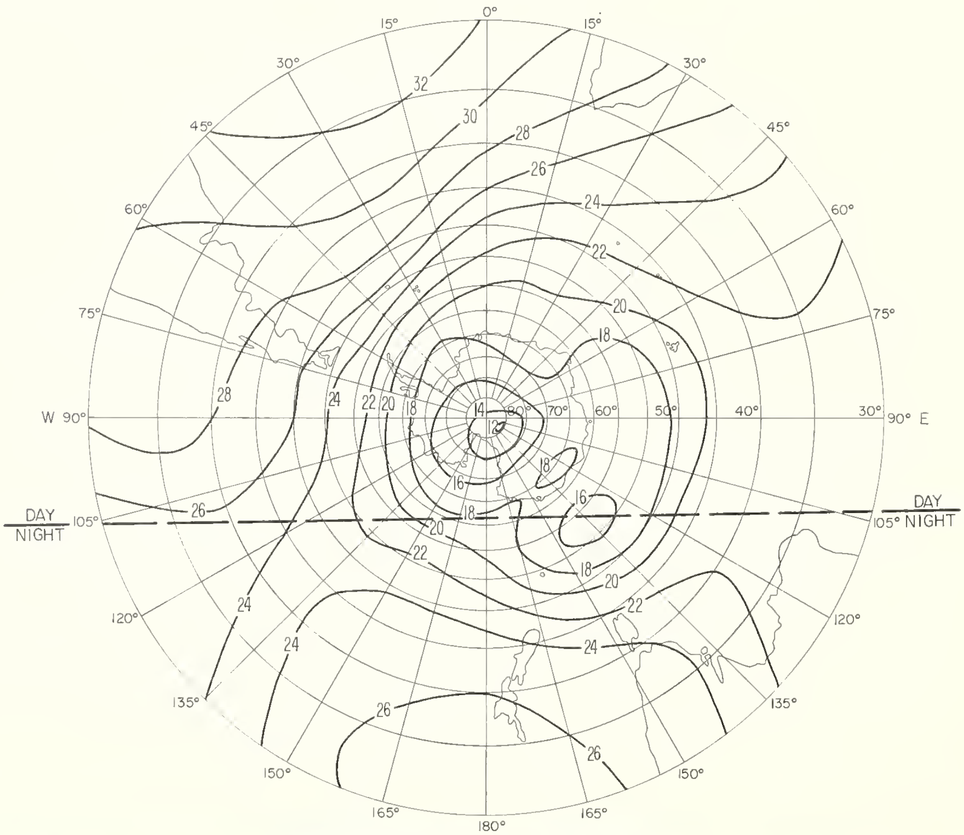


FIG. 18B. MEDIAN F2-4000-MUF (Mc/s)

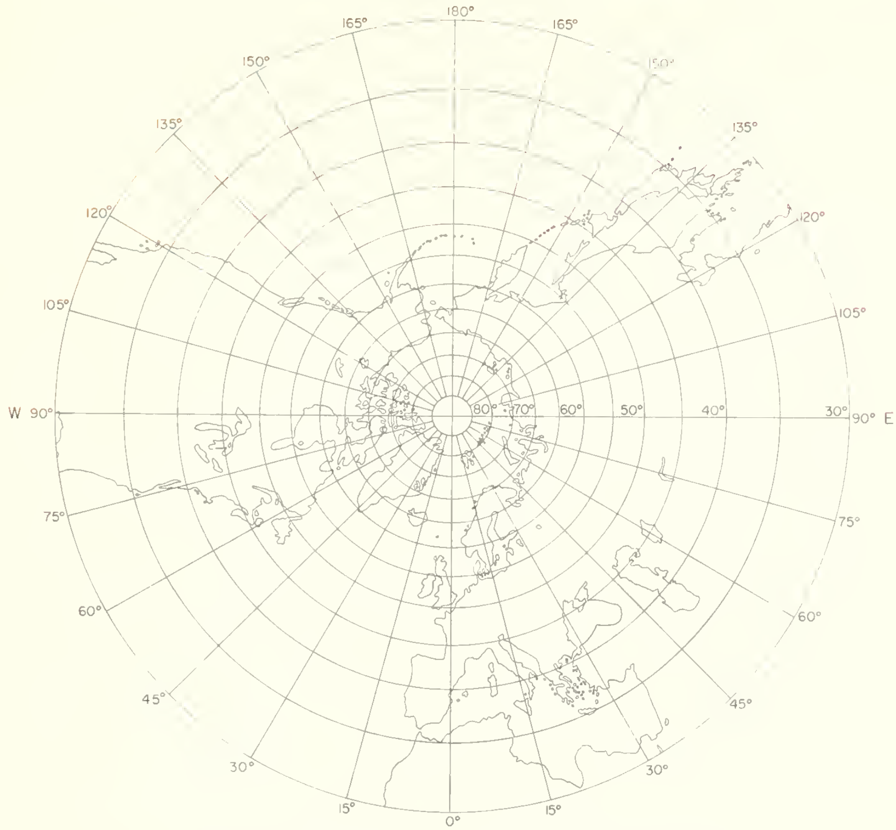


FIG. 19. NORTH POLAR AREA, GNOMONIC PROJECTION

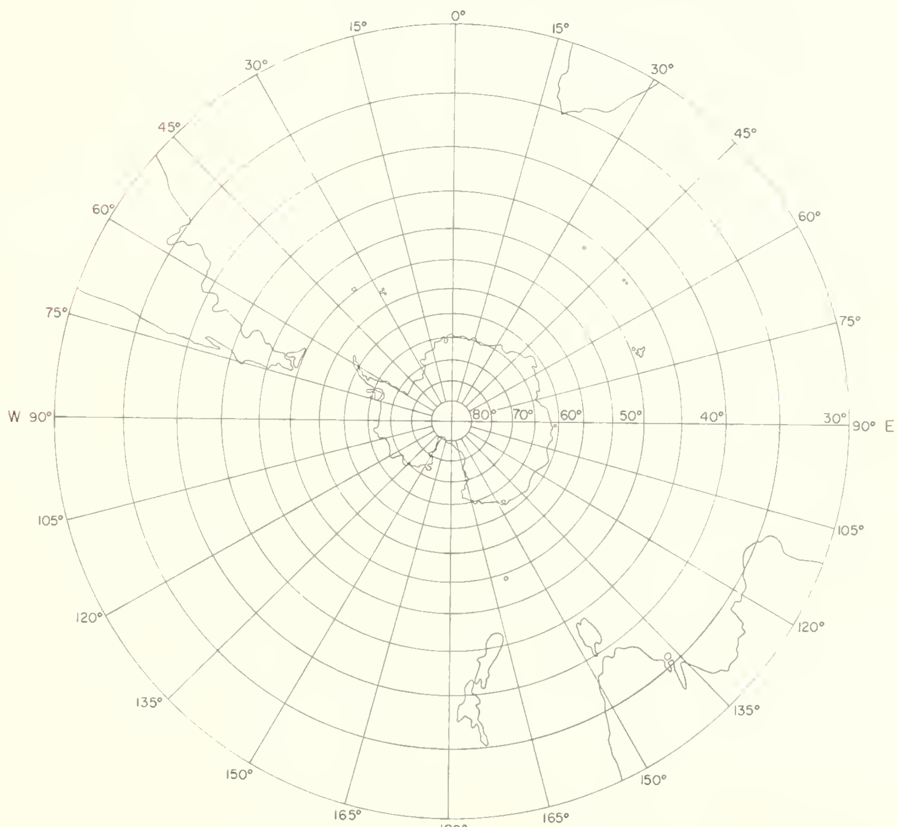


FIG. 20. SOUTH POLAR AREA, GNOMONIC PROJECTION

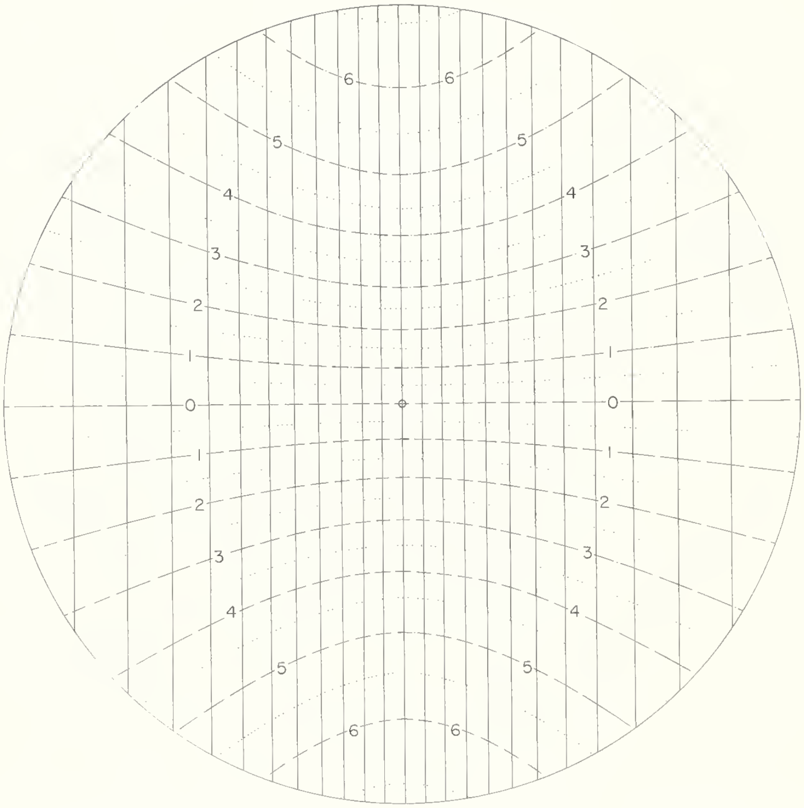


FIG. 21. GREAT CIRCLE CHART FOR POLAR GNOMONIC PROJECTION MAPS
(SOLID LINES REPRESENT GREAT CIRCLES. NUMBERED DOT – DASH LINES INDICATE DISTANCE IN THOUSANDS OF KILOMETERS.)

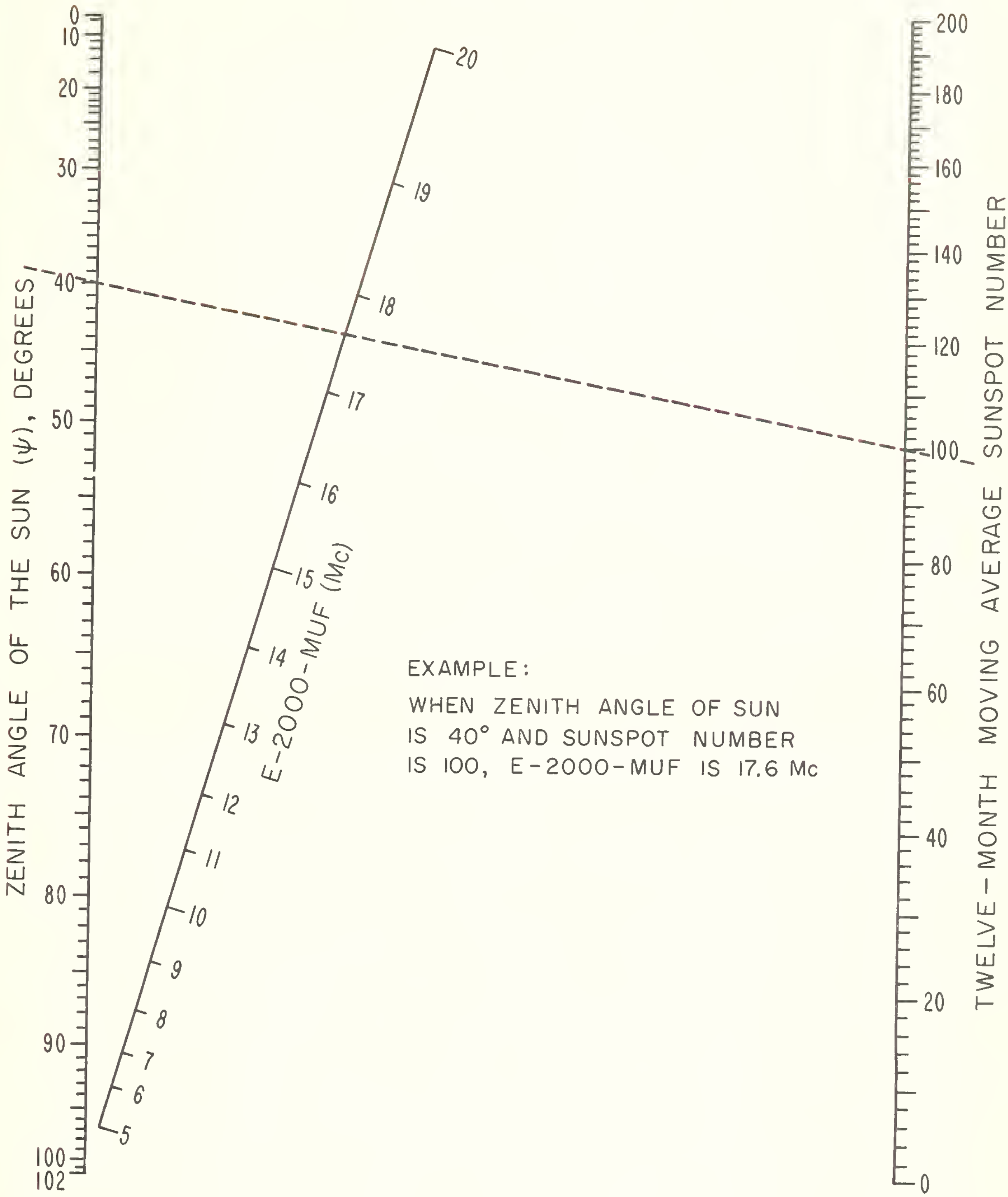


FIGURE 22. NOMOGRAM FOR OBTAINING E-LAYER 2000-MUF FROM 12-MONTH MOVING AVERAGE SUNSPOT NUMBER AND THE ZENITH ANGLE OF THE SUN.

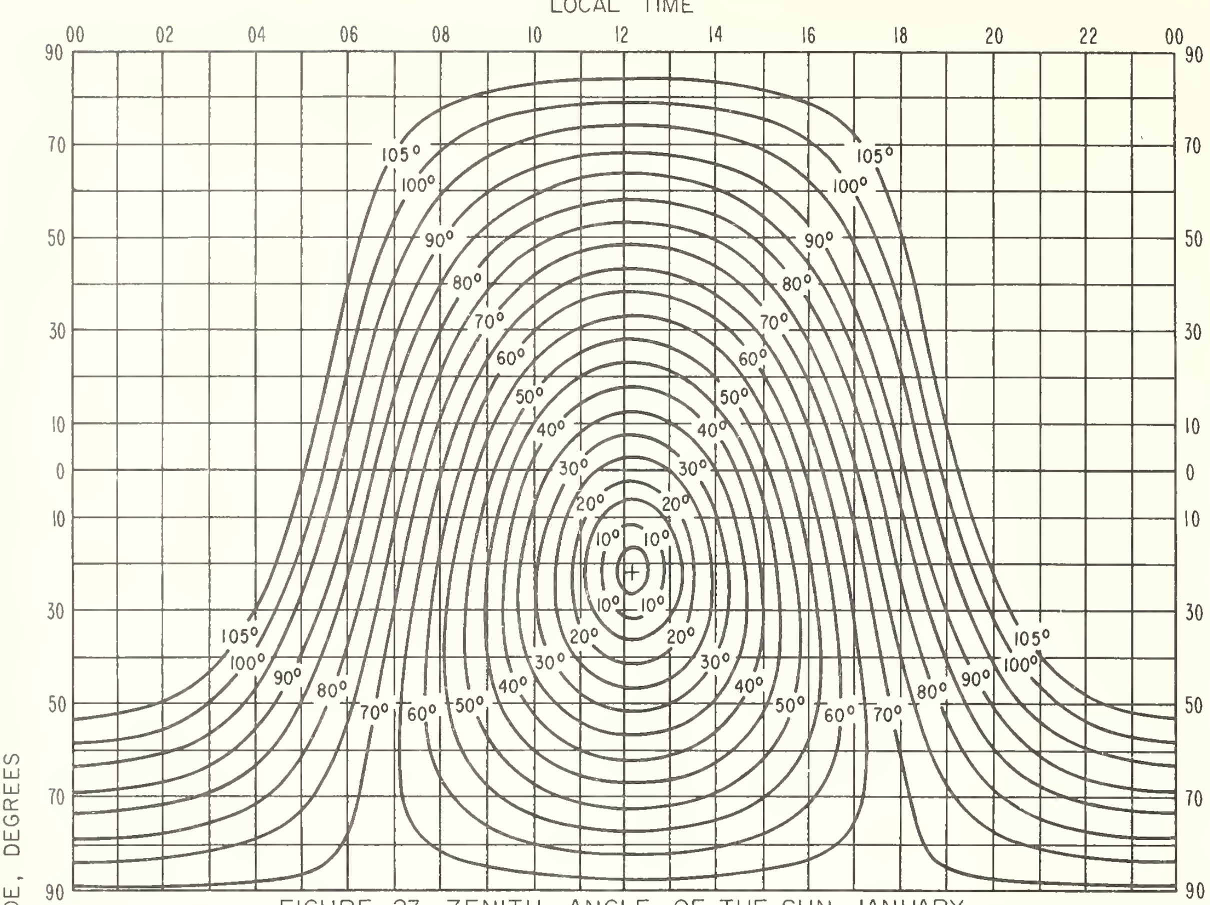


FIGURE 23. ZENITH ANGLE OF THE SUN, JANUARY

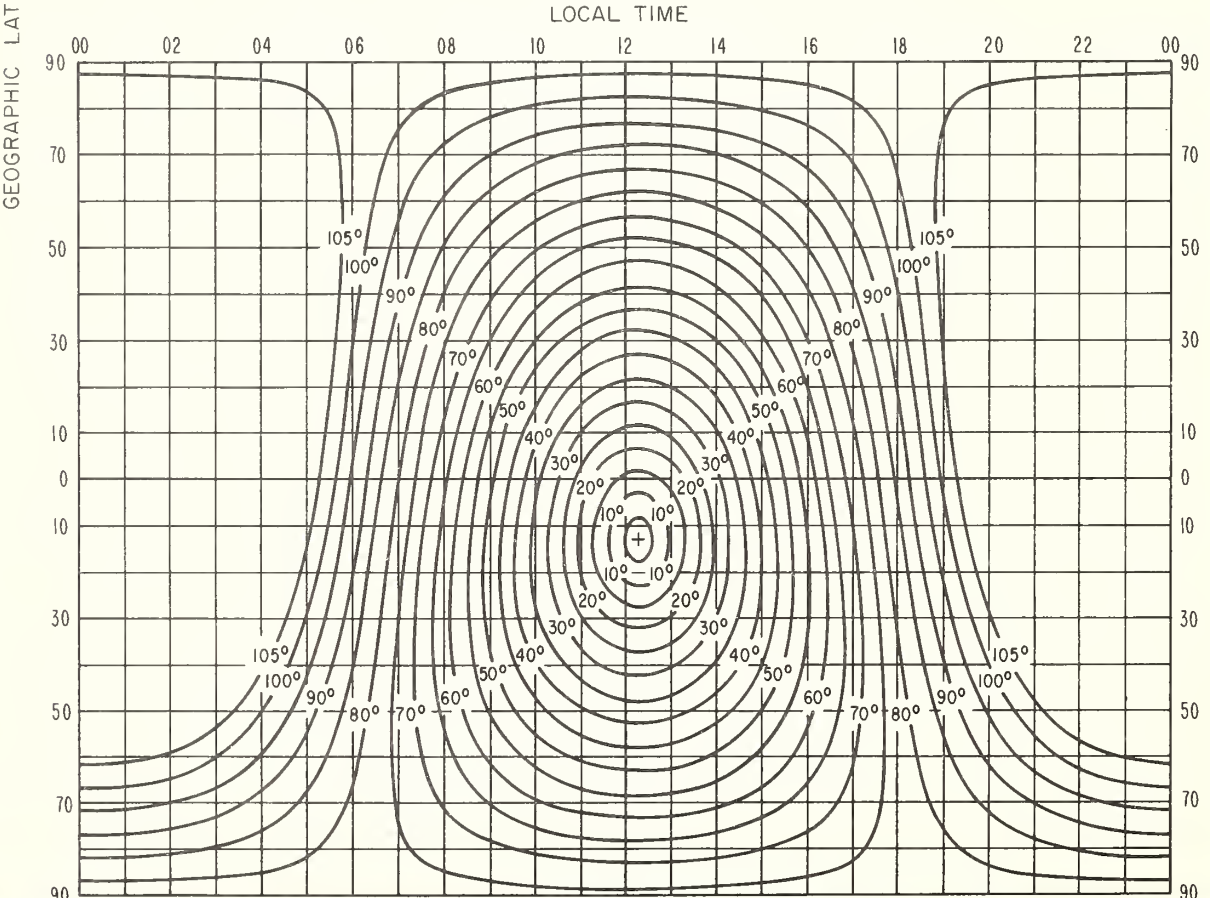


FIGURE 24. ZENITH ANGLE OF THE SUN, FEBRUARY

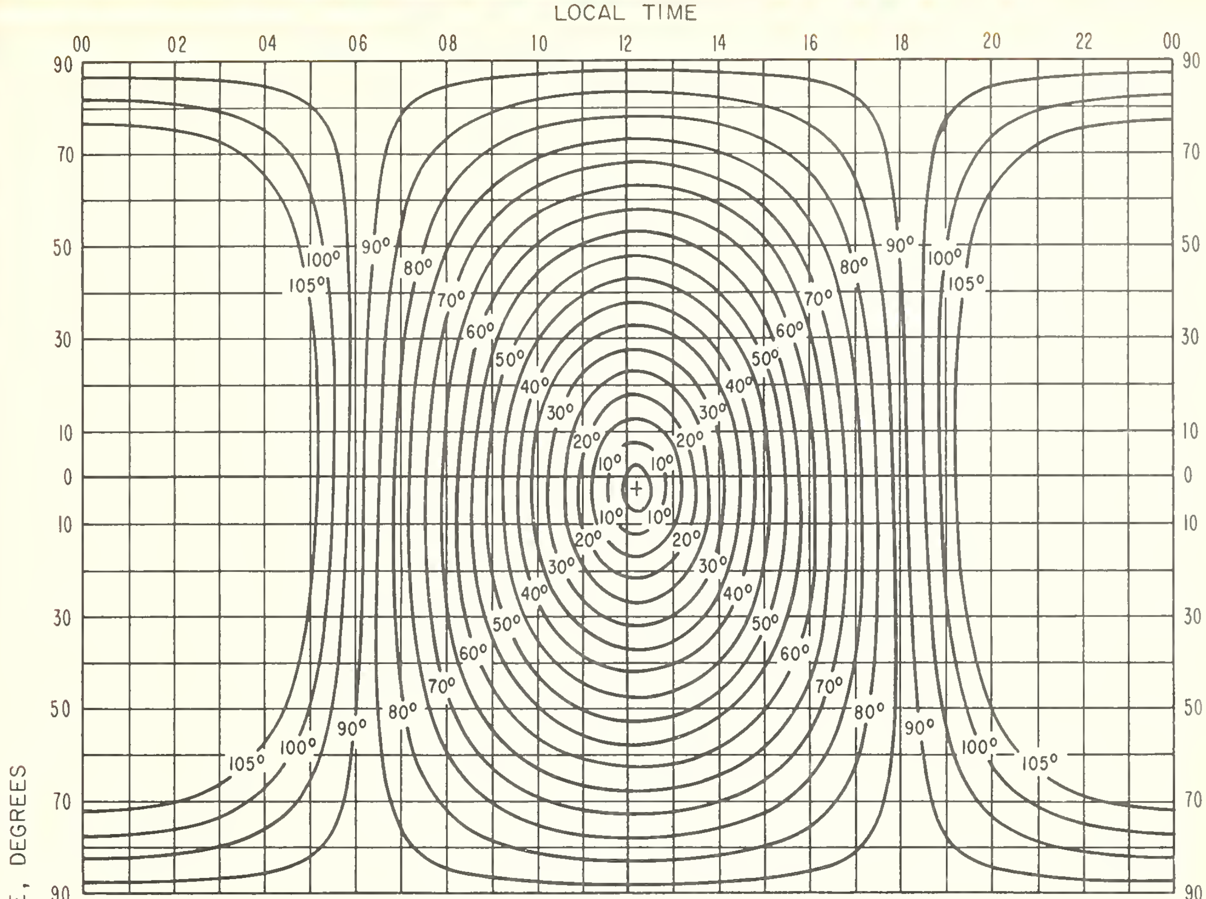


FIGURE 25. ZENITH ANGLE OF THE SUN, MARCH

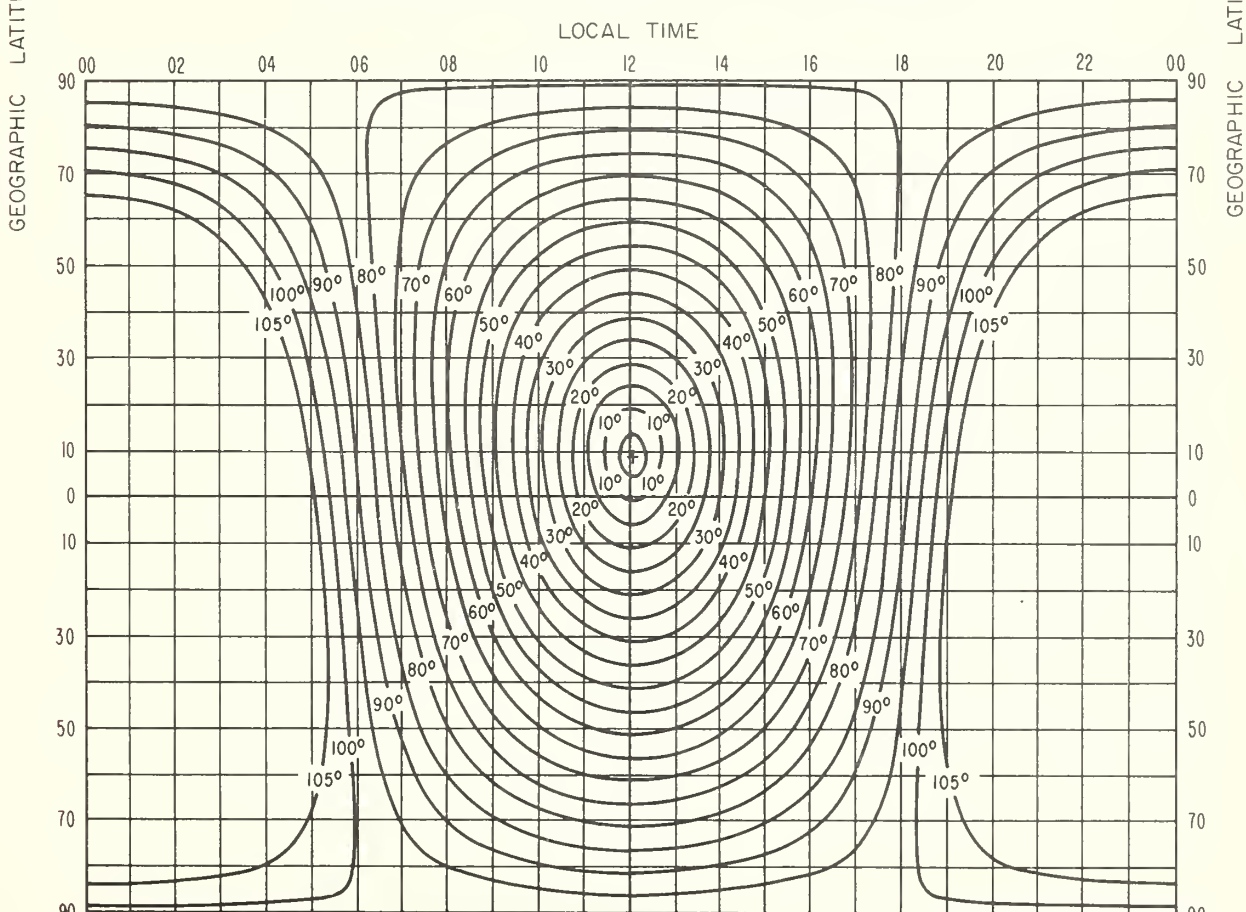


FIGURE 26. ZENITH ANGLE OF THE SUN, APRIL

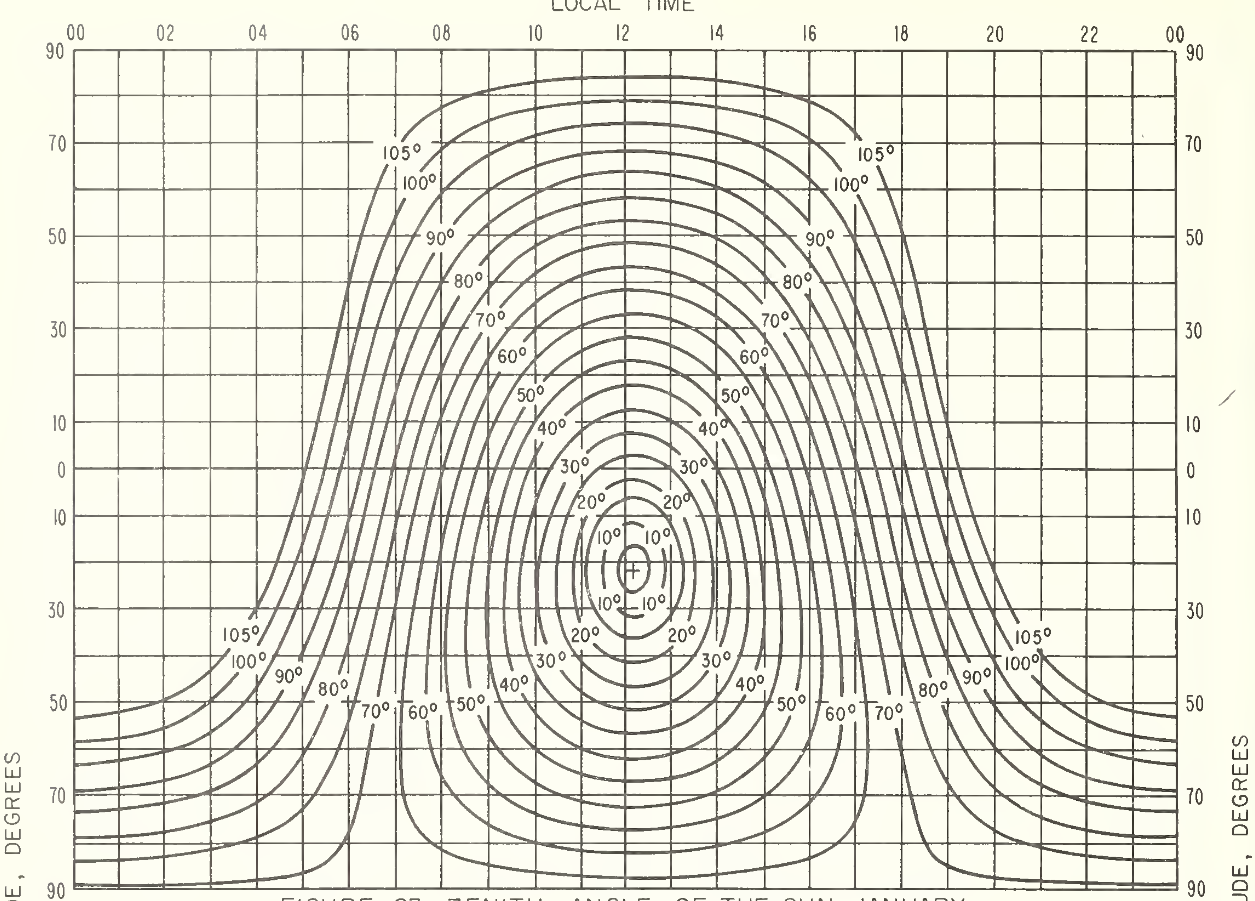


FIGURE 23. ZENITH ANGLE OF THE SUN, JANUARY

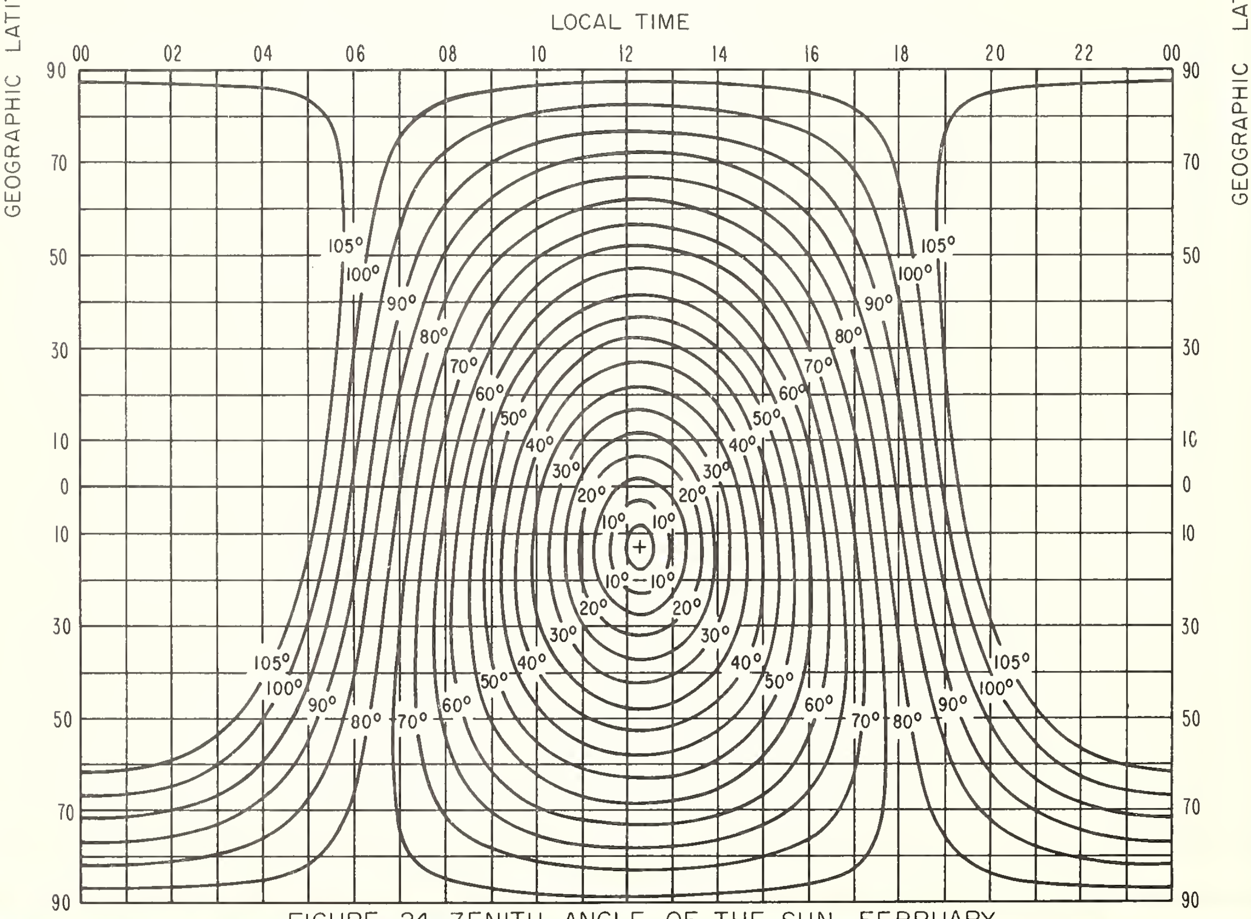


FIGURE 24. ZENITH ANGLE OF THE SUN, FEBRUARY

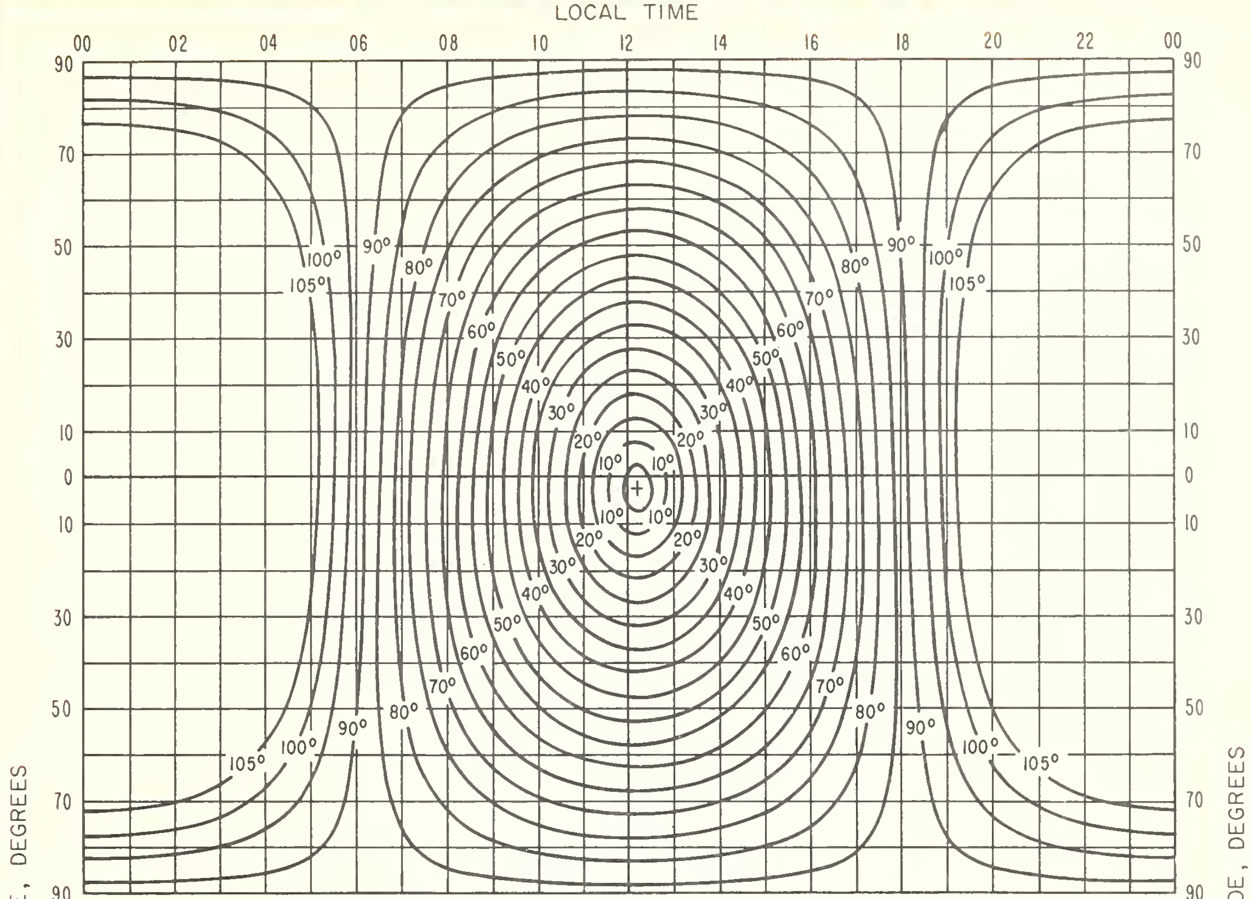


FIGURE 25. ZENITH ANGLE OF THE SUN, MARCH

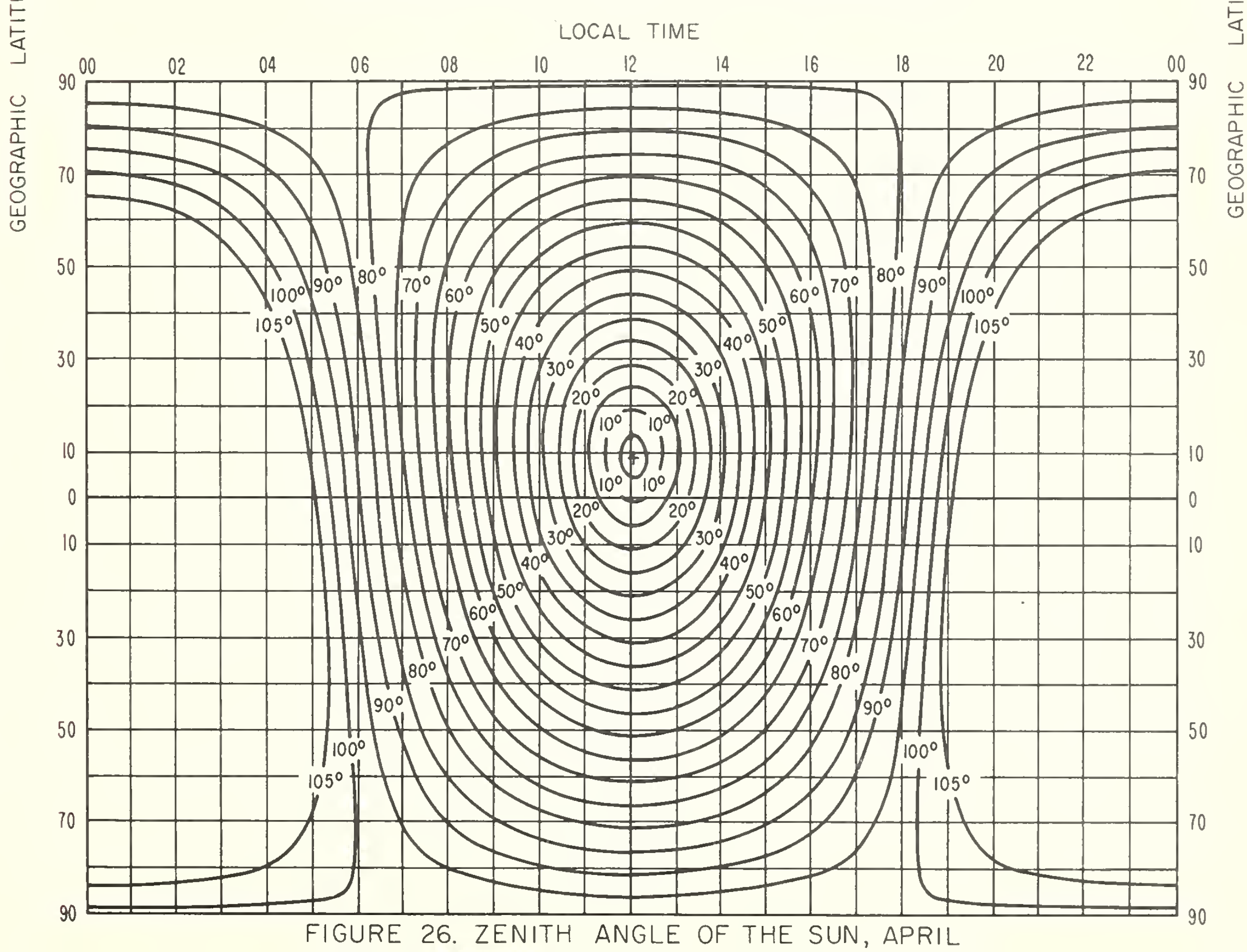


FIGURE 26. ZENITH ANGLE OF THE SUN, APRIL

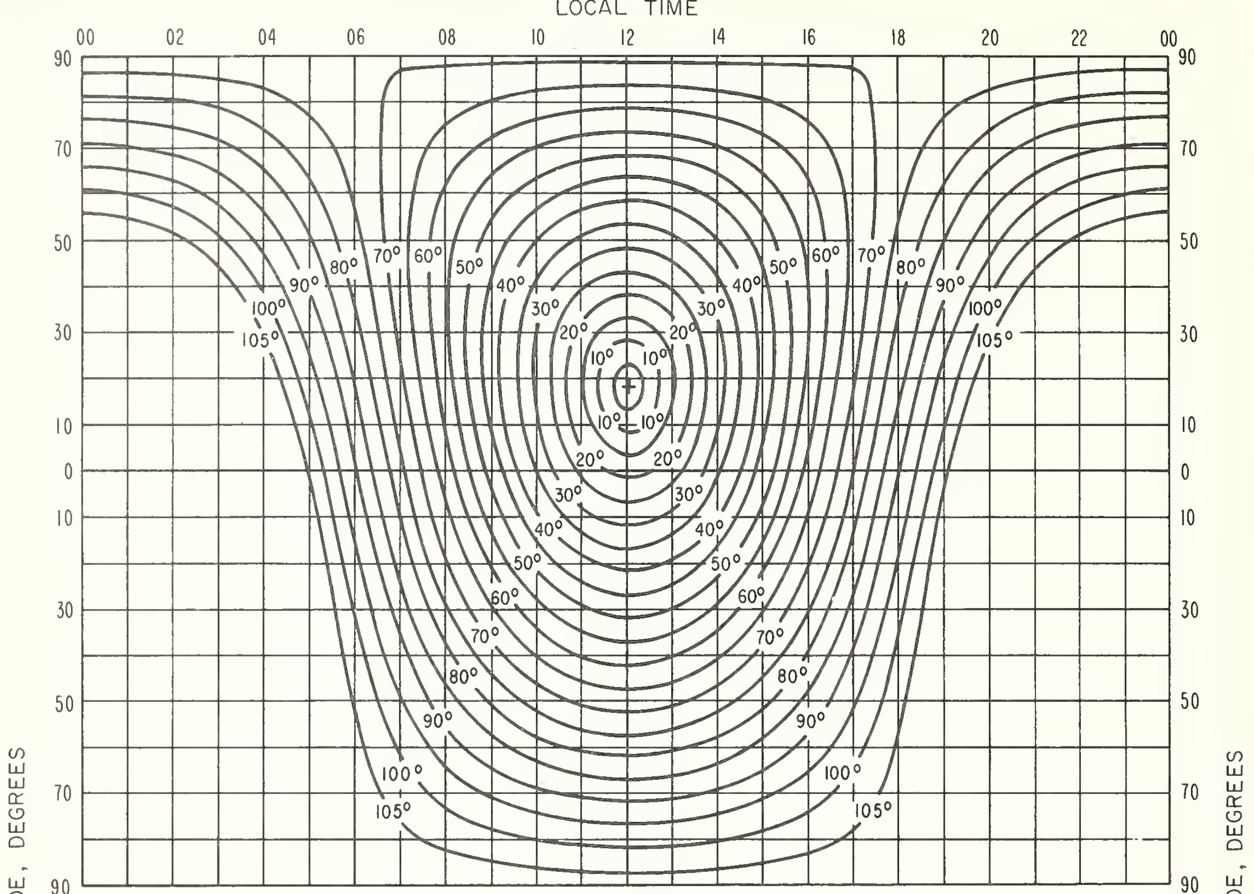


FIGURE 27. ZENITH ANGLE OF THE SUN, MAY

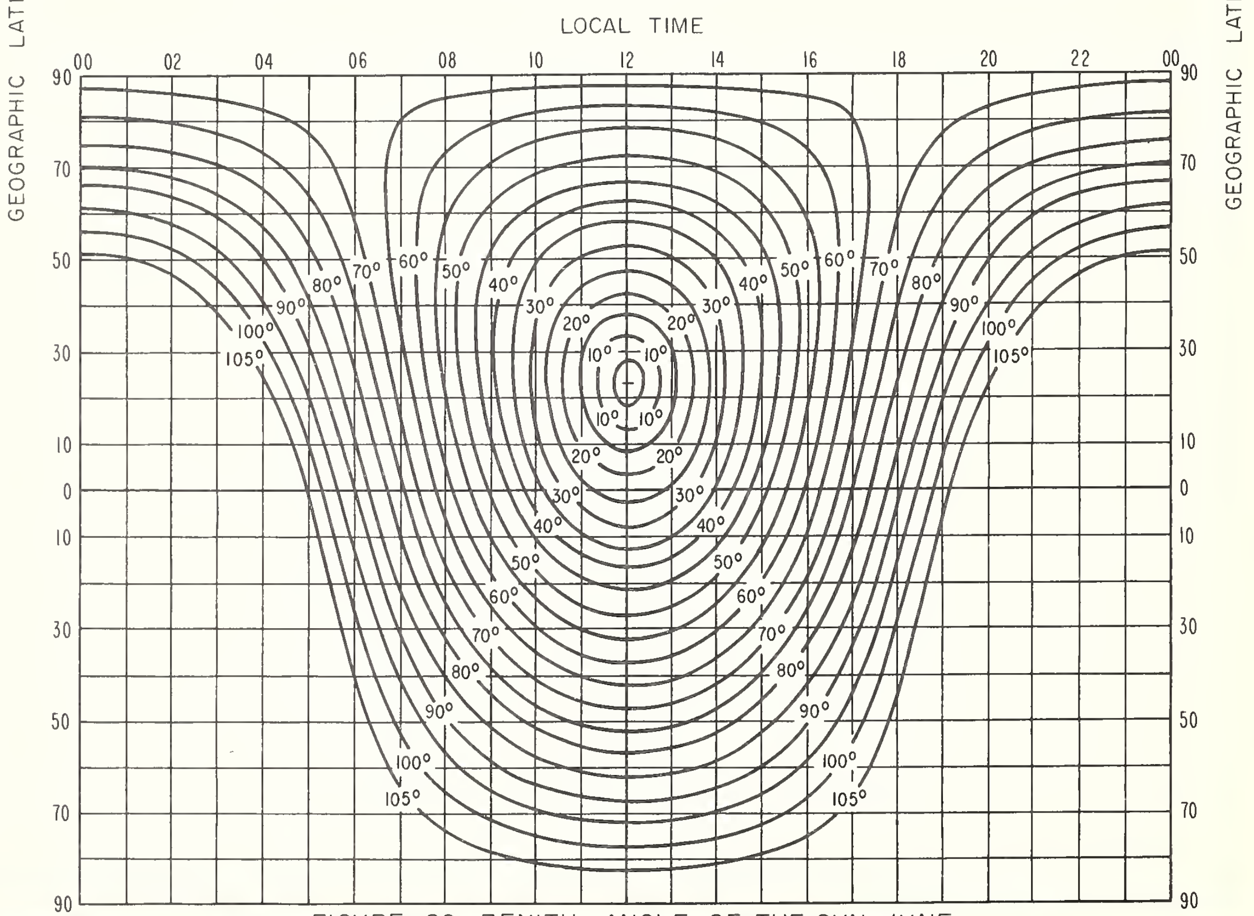


FIGURE 28. ZENITH ANGLE OF THE SUN, JUNE

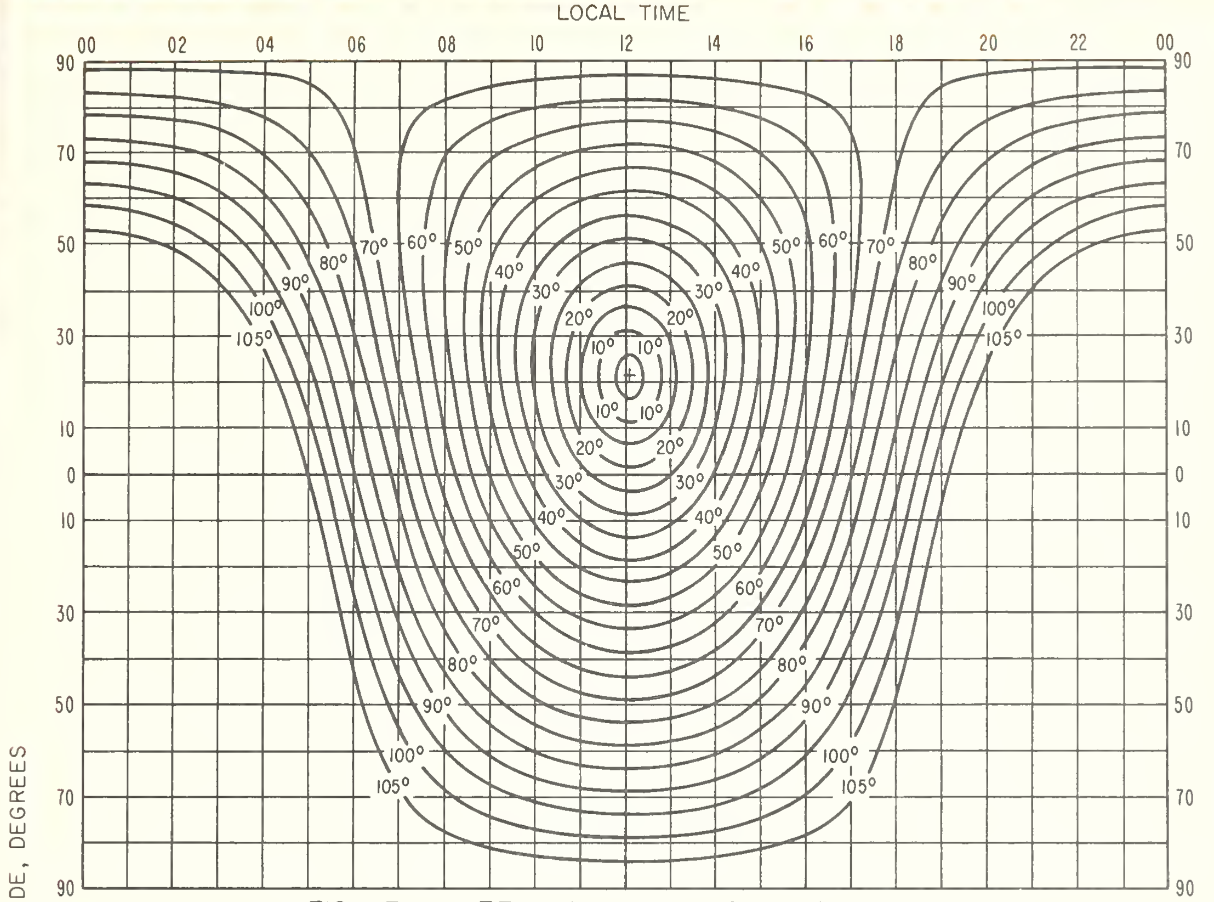


FIGURE 29. ZENITH ANGLE OF THE SUN, JULY

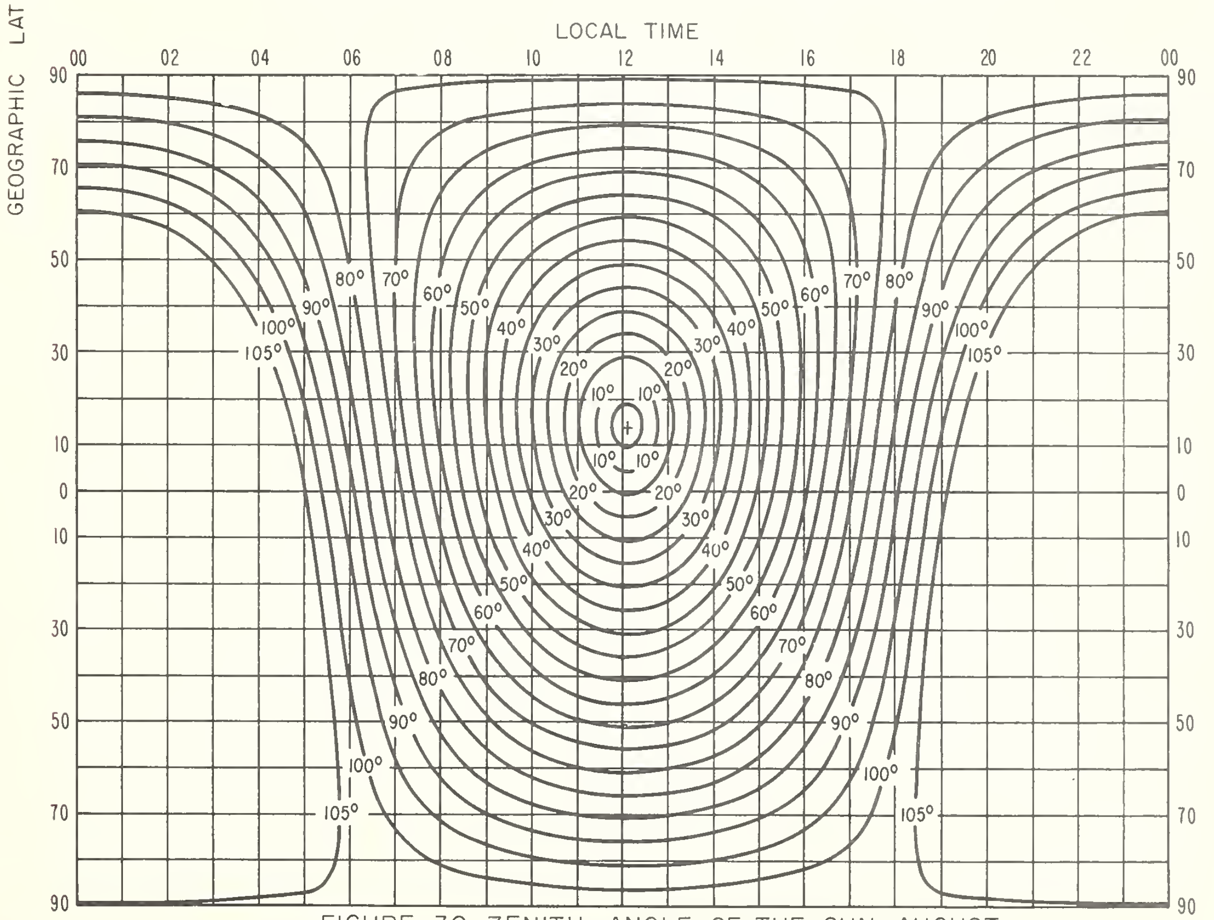


FIGURE 30. ZENITH ANGLE OF THE SUN, AUGUST

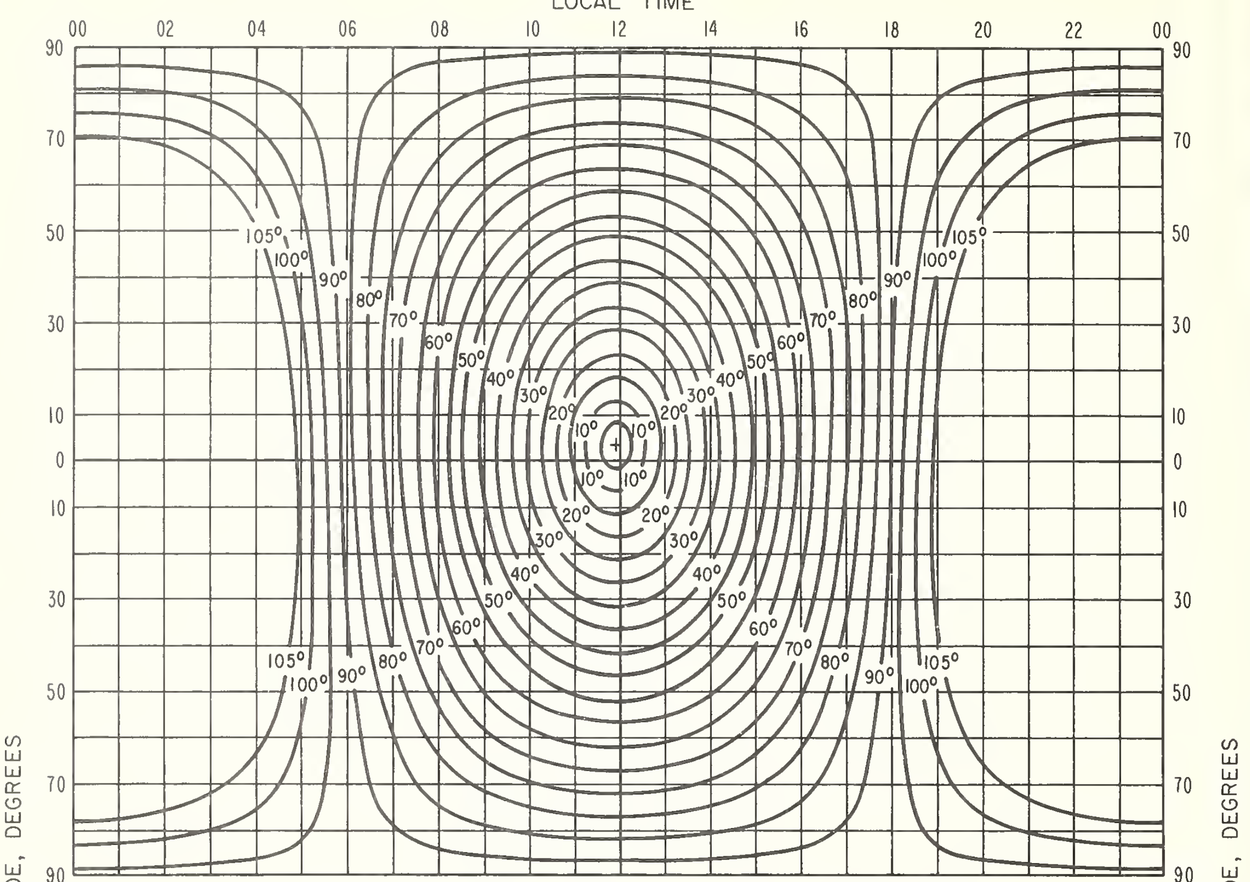


FIGURE 31. ZENITH ANGLE OF THE SUN, SEPTEMBER

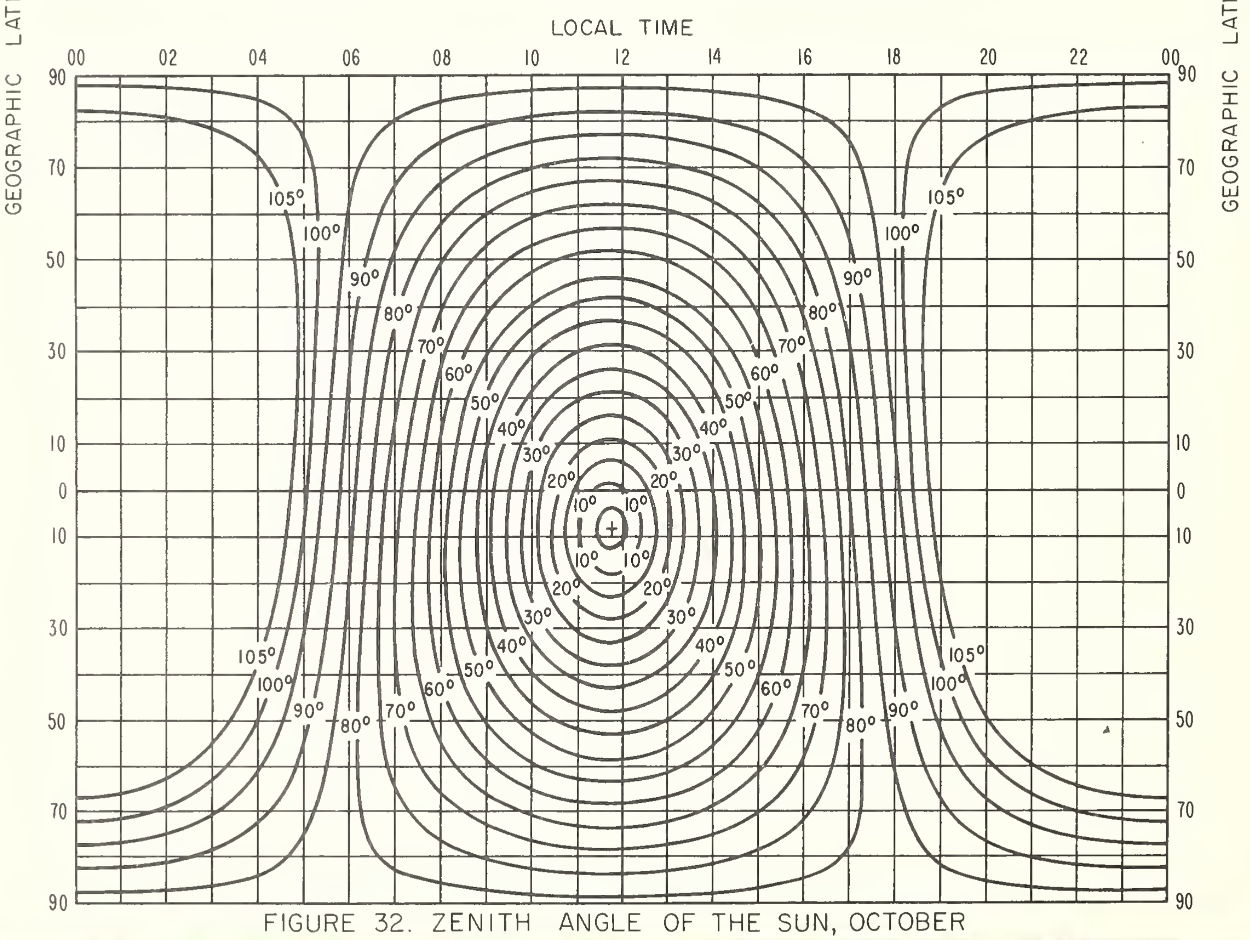


FIGURE 32. ZENITH ANGLE OF THE SUN, OCTOBER

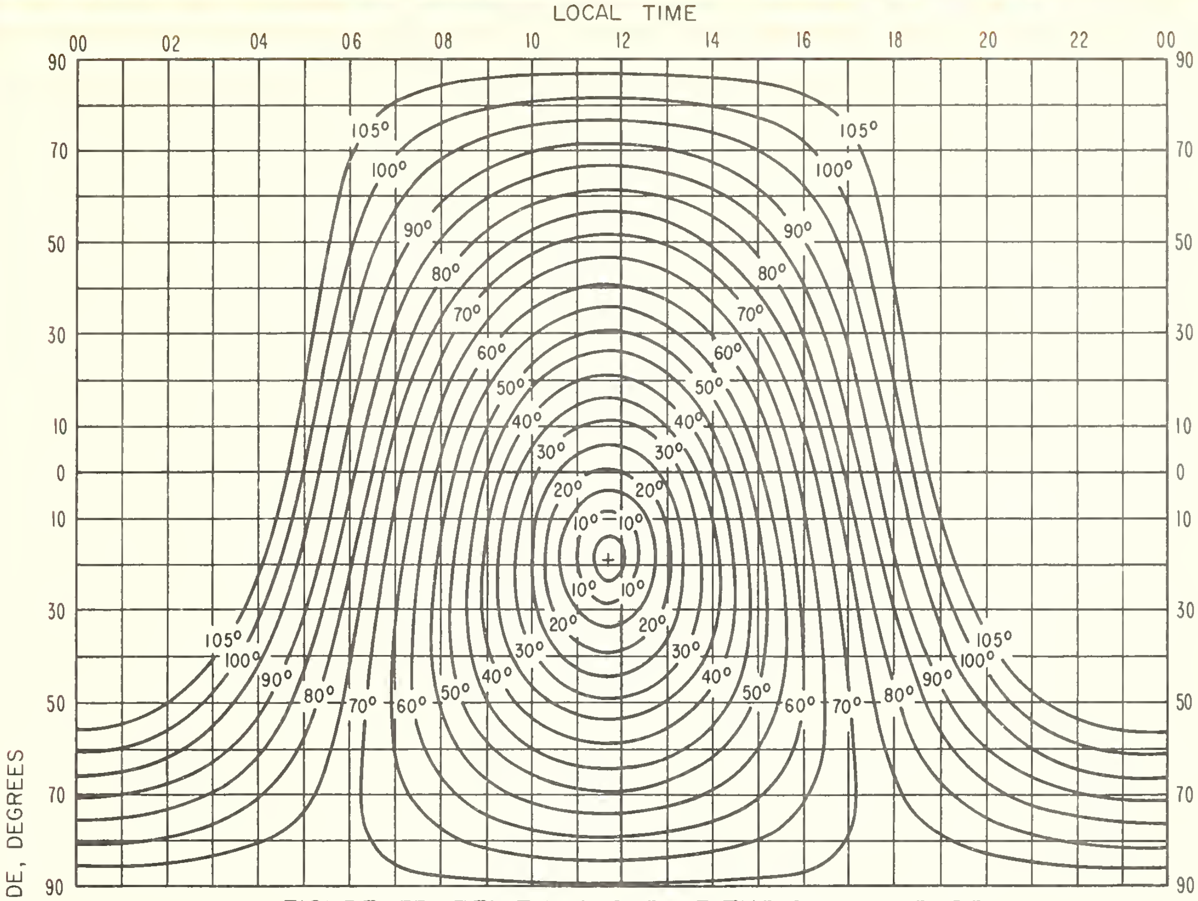


FIGURE 33. ZENITH ANGLE OF THE SUN, NOVEMBER

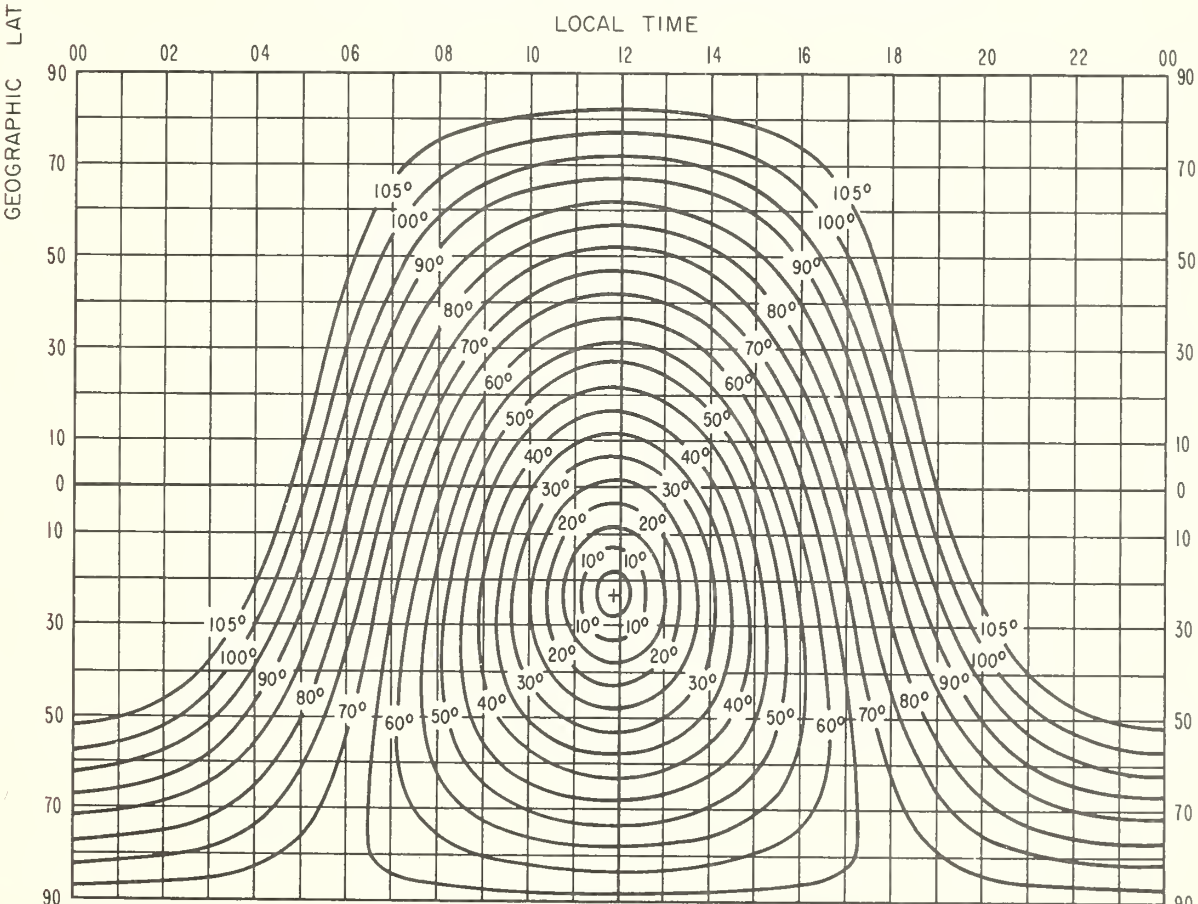


FIGURE 34. ZENITH ANGLE OF THE SUN, DECEMBER

FIG. 35. EXAMPLES OF GREAT CIRCLE TRANSMISSION PATHS, MARKED ON WORLD MAP.

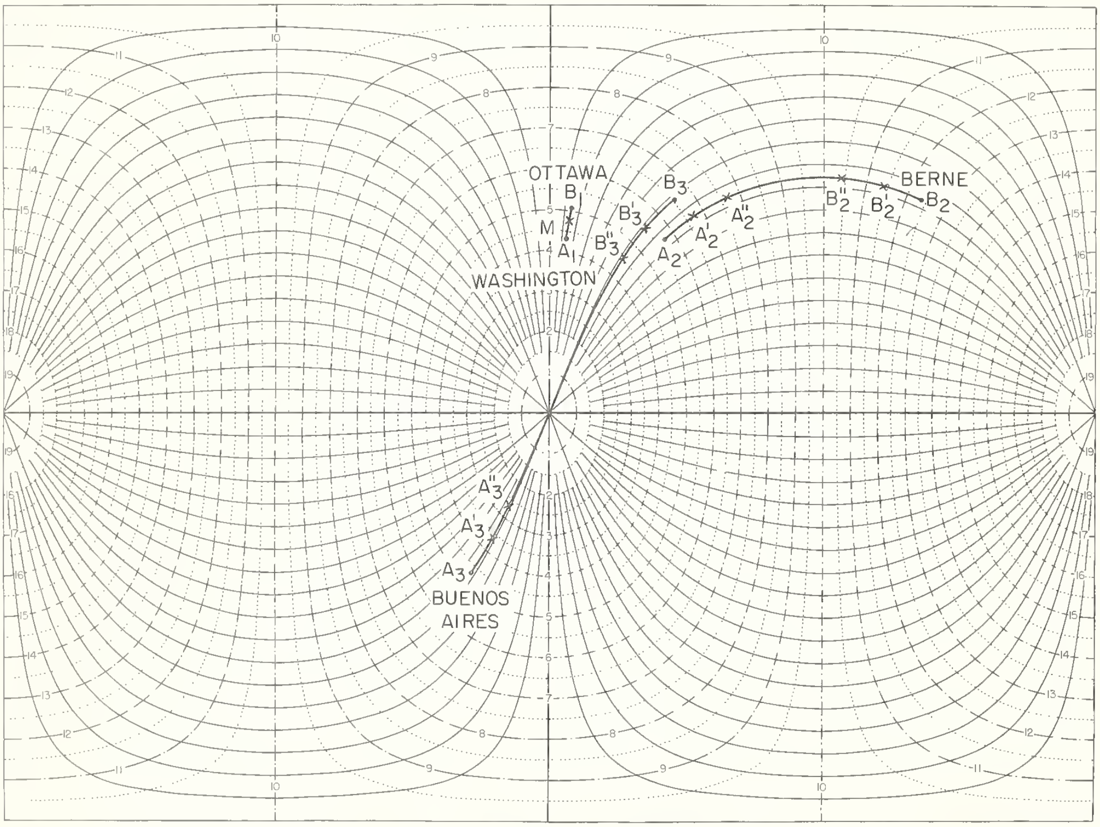


FIG. 36. EXAMPLES OF PATHS MARKED ON WORLD GREAT CIRCLE CHART.

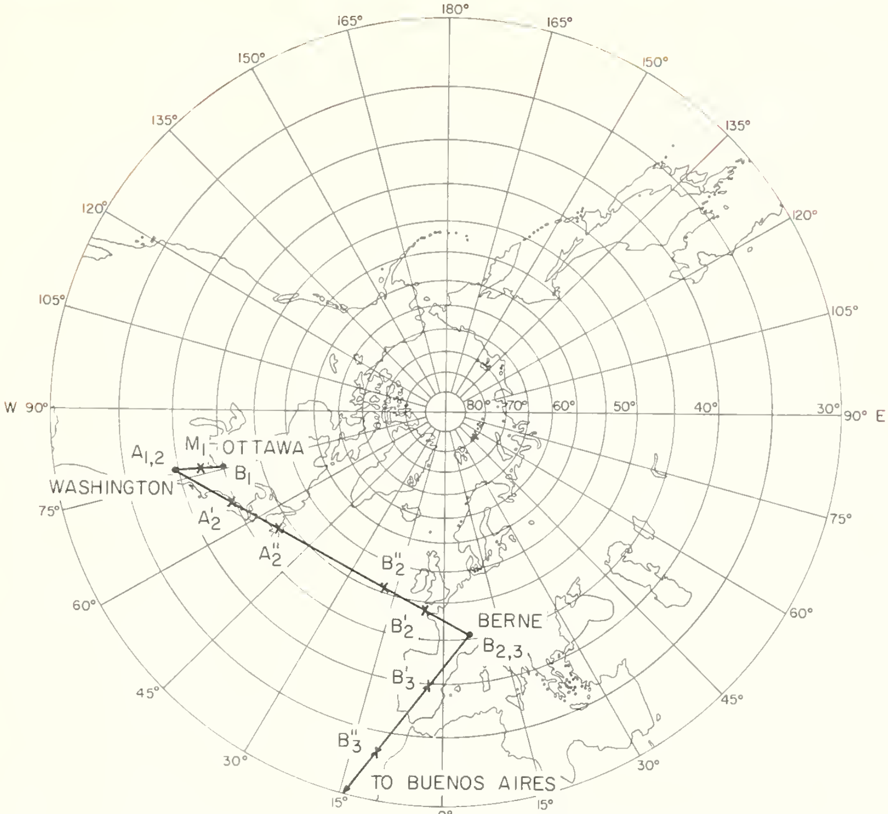


FIG. 37. EXAMPLES OF GREAT CIRCLE TRANSMISSION PATHS, MARKED ON NORTH POLAR AREA GNOMONIC MAP.

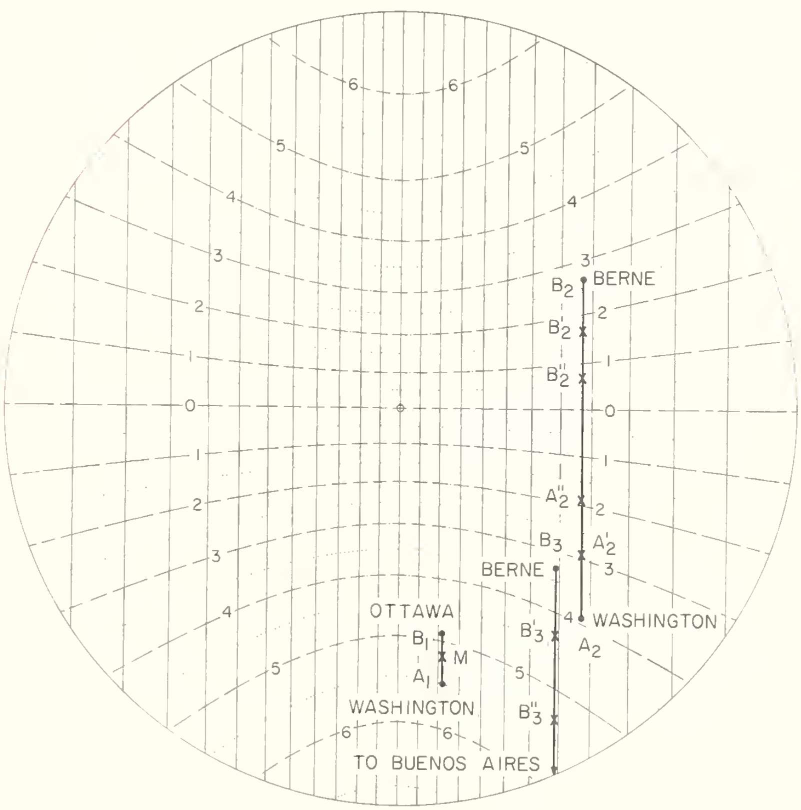


FIG. 38. EXAMPLES OF PATHS MARKED ON POLAR GNOMONIC GREAT CIRCLE CHART.

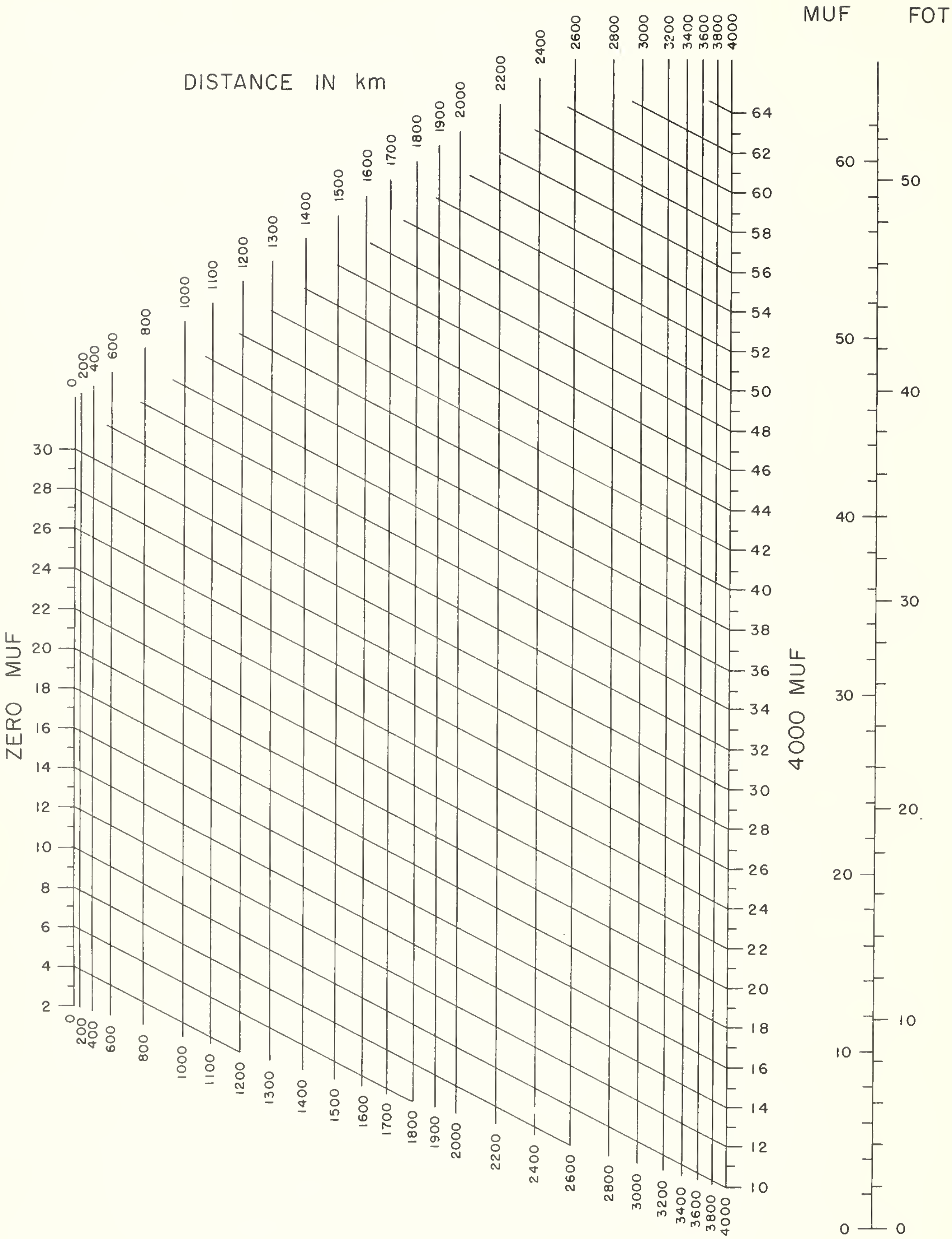


FIG. 39. NOMOGRAM FOR TRANSFORMING F2-ZERO-MUF AND F2-4000-MUF TO EQUIVALENT MAXIMUM USABLE FREQUENCIES AT INTERMEDIATE TRANSMISSION DISTANCES; CONVERSION SCALE FOR OBTAINING OPTIMUM WORKING FREQUENCY (FOT).

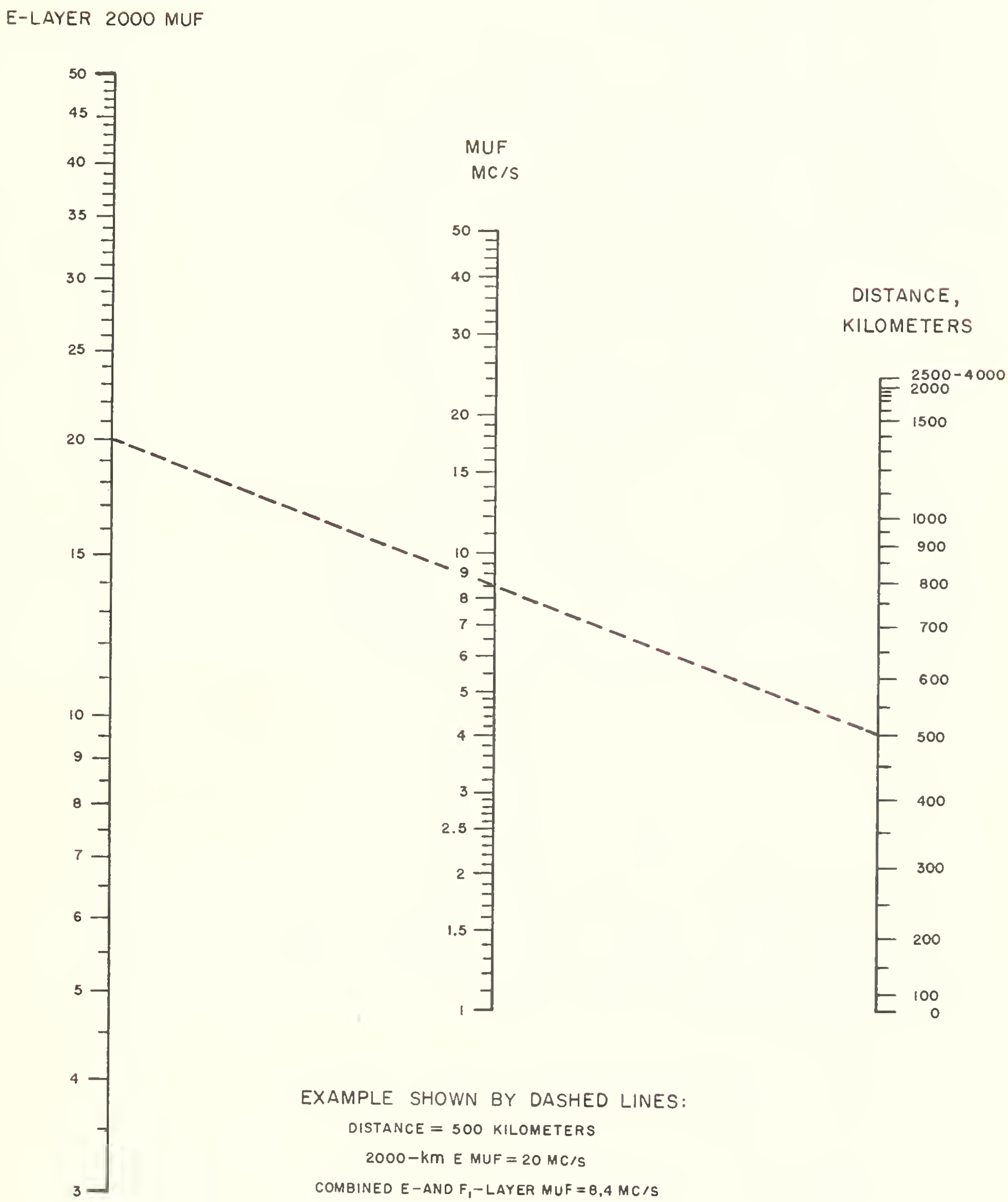


FIG. 40. NOMOGRAM FOR TRANSFORMING E-LAYER 2000-MUF TO EQUIVALENT MAXIMUM USABLE FREQUENCIES AND OPTIMUM WORKING FREQUENCIES. THE F_1 LAYER IS APPROXIMATELY ACCOUNTED FOR AT DISTANCES BETWEEN 2000 AND 4000 km.

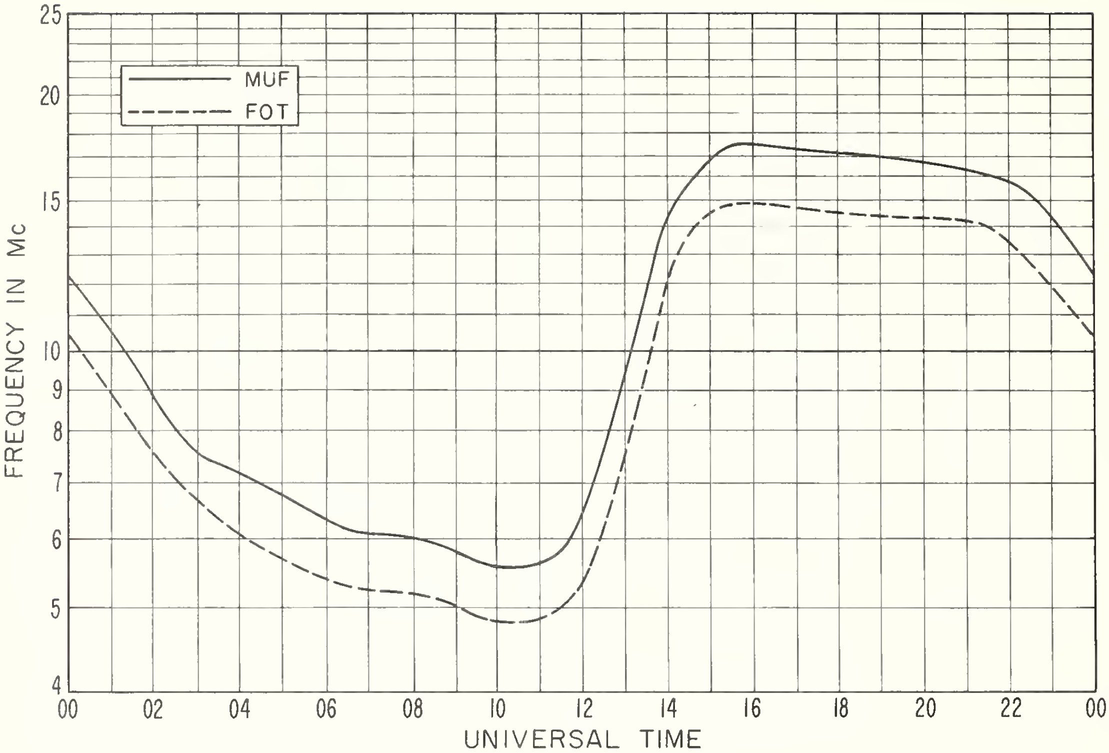


Figure 41. EXAMPLE 1. SHORT PATH. DECEMBER 1958. DISTANCE: 750 km
A_1, WASHINGTON (39° N, 78° W) TO B_1, OTTAWA (45° N, 76° W)

Table 4

Example 1. Short Path. December 1958.

A_1, Washington (39°N, 78°W) to B_1, Ottawa (45°N, 76°W). Distance 750 km.

UT	F2-zero-MUF	F2-4000-MUF	Path F2-MUF	Solar zenith angle	E-2000-MUF	Path E-MUF	Path MUF	Path F2-FOT	Path FOT
00	10.3	30.6	12.2				12.2	10.4	10.4
02	7.5	21.0	8.8				8.8	7.5	7.5
04	6.2	16.0	7.2				7.2	6.1	6.1
06	5.7	14.6	6.3				6.3	5.4	5.4
08	5.4	13.8	6.1				6.1	5.2	5.2
10	5.0	12.4	5.6				5.6	4.8	4.8
12	5.7	16.0	6.4	95°	6.5	3.8	6.4	5.4	5.4
14	12.0	39.0	14.3	78°	12.8	7.4	14.3	12.2	12.2
16	14.5	45.4	17.6	67°	15.2	8.8	17.6	15.0	15.0
18	14.5	43.6	17.2	67°	15.2	8.8	17.2	14.6	14.6
20	14.3	42.4	16.9	77°	13.1	7.6	16.9	14.4	14.4
22	13.4	40.0	15.9	94°	7.1	4.1	15.9	13.5	13.5

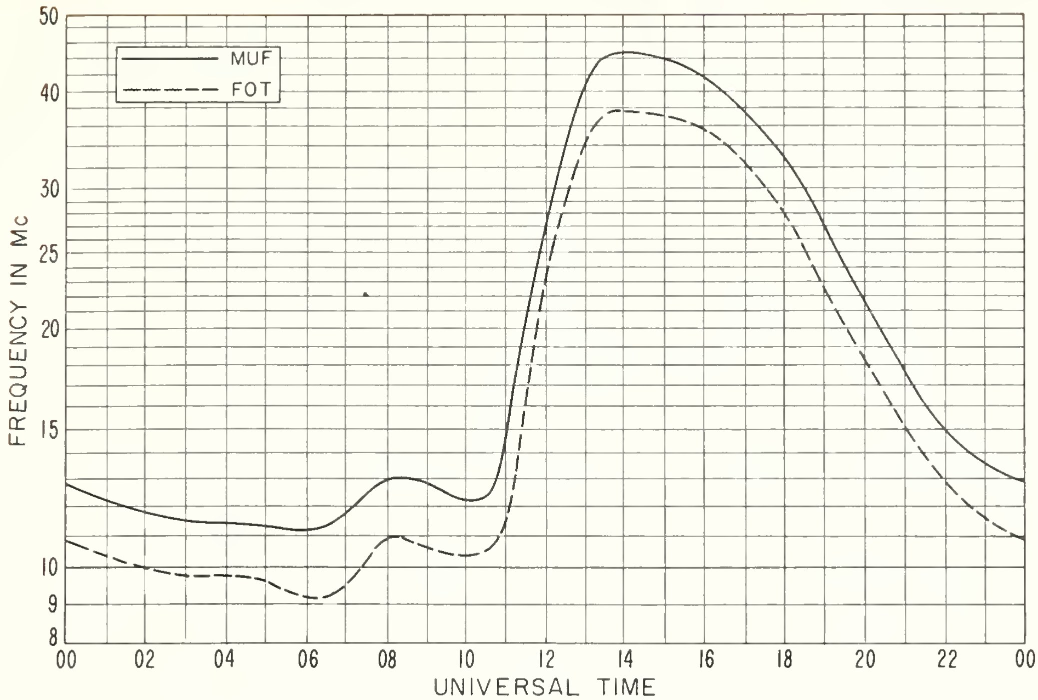


Figure 42. EXAMPLE 2. LONG PATH. DECEMBER 1958. DISTANCE: 7,200 km
A_2, WASHINGTON (39°N, 78°W) TO B_2, BERNE (47°N, 7°E)

Table 5

Example 2. Long Path. December 1958.

A_2, Washington (39°N, 78°W) to B_2, Berne (47°N, 7°E) Distance 7,200 km.

UT	A_2'' F2-4000-MUF	B_2'' F2-4000-MUF	A_2' Solar zenith angle	B_2' Solar zenith angle	A_2' E-2000-MUF	B_2' E-2000-MUF	A_2 MUF	B_2 MUF	Path MUF	A_2'' F2-FOT	B_2'' F2-FOT	A_2 FOT	B_2 FOT	Path FOT
00	19.7	12.8					19.7	12.8	12.8	16.7	10.9	16.7	10.9	10.9
02	15.2	11.8					15.2	11.8	11.8	12.9	10.0	12.9	10.0	10.0
04	13.4	11.5					13.4	11.5	11.5	11.4	9.8	11.4	9.8	9.8
06	12.9	11.2					12.9	11.2	11.2	11.0	9.2	11.0	9.2	9.2
08	13.0	13.2		92°		8.0	13.0	13.2	13.0	11.0	11.2	11.0	11.2	11.0
10	12.2	32.2		78°		12.8	12.2	32.2	12.2	10.4	27.4	10.4	27.4	10.4
12	27.9	44.6	90°	72°	8.8	14.2	27.9	44.6	27.9	23.7	37.9	23.7	37.9	23.7
14	44.5	45.0	75°	76°	13.6	13.3	44.5	45.0	44.5	37.8	38.2	37.8	38.2	37.8
16	46.8	41.8	67°	87°	15.2	10.0	46.8	41.8	41.8	39.8	35.5	39.8	35.5	35.5
18	45.2	33.0	70°	105°	14.6		45.2	33.0	33.0	38.4	28.0	38.4	28.0	28.0
20	40.0	21.5	82°		11.6		40.0	21.5	21.5	34.0	18.3	34.0	18.3	18.3
22	29.6	15.0	101°				29.6	15.0	15.0	25.2	12.8	25.2	12.8	12.8

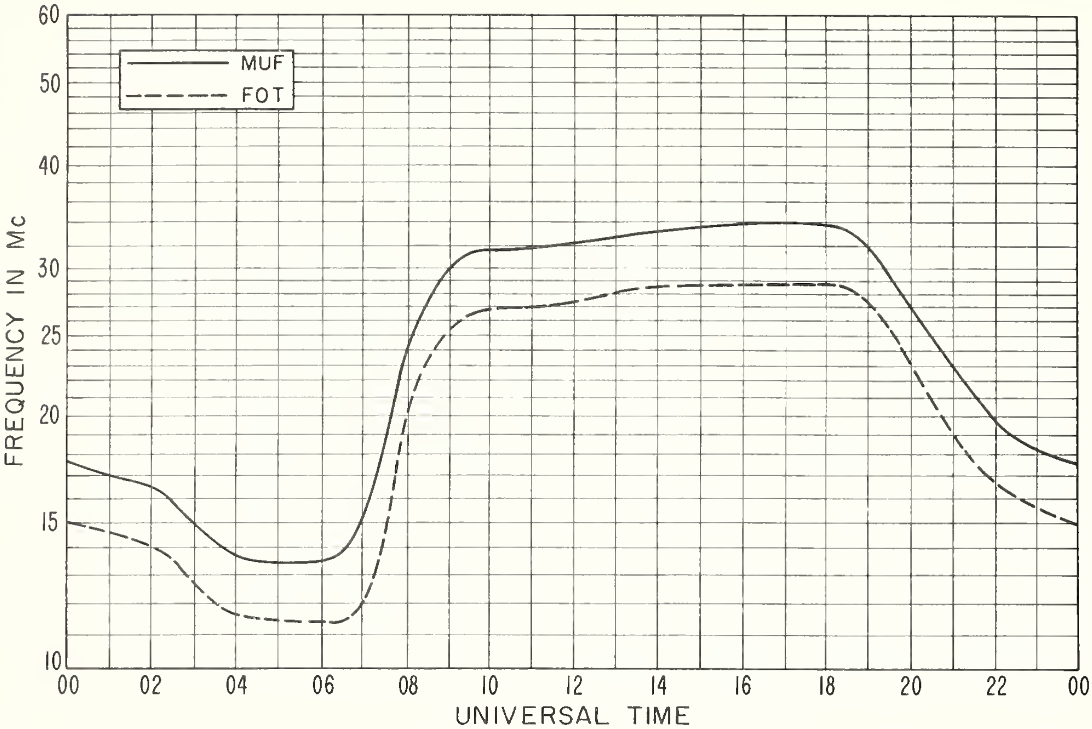


Figure 43. EXAMPLE 3. LONG PATH. DECEMBER 1958. DISTANCE: 11,200km
A_3, BUENOS AIRES(35°S, 59°W) TO B_3, BERNE (47°N, 7°E)

Table 6

Example 3. Long Path. December 1958.

A3 , Buenos Aires (35°S, 59°W) to B3, Berne (47°N, 7°E) Distance 11,200 km.

UT	A3'' F2-4000-MUF	B3'' F2-4000-MUF	A3' Solar zenith angle	B3' Solar zenith angle	A3' E-2000-MUF	B3' E-2000 MUF	A3 MUF	B3 MUF	Path MUF	A3'' F2-FOT	B3'' F2-FOT	A3 FOT	B3 FOT	Path FOT
00	27.2	17.6					27.2	17.6	17.6	23.1	15.0	23.1	15.0	15.0
02	27.9	16.6					27.9	16.6	16.6	23.7	14.1	23.7	14.1	14.1
04	27.6	13.8					27.6	13.8	13.8	23.5	11.7	23.5	11.7	11.7
06	26.2	13.5		104°			26.2	13.5	13.5	22.3	11.5	22.3	11.5	11.5
08	24.2	30.0	95°	84°	6.5	10.9	24.2	30.0	24.2	20.6	25.5	20.6	25.5	20.6
10	31.6	46.6	71°	66°	14.4	15.4	31.6	46.6	31.6	26.9	39.6	26.9	39.6	26.9
12	32.2	44.0	45°	57°	18.3	16.8	32.2	44.0	32.2	27.4	37.4	27.4	37.4	27.4
14	33.6	42.7	23°	61°	19.6	16.3	33.6	42.7	33.6	28.6	36.3	28.6	36.3	28.6
16	33.7	42.2	10°	76°	19.9	13.3	33.7	42.2	33.7	28.6	35.9	28.6	35.9	28.6
18	34.0	38.0	35°	98°	19.1	5.2	34.0	38.0	34.0	28.9	32.3	28.9	32.3	28.9
20	33.0	27.4	63°		15.9		33.0	27.4	27.4	28.0	23.3	28.0	23.3	23.3
22	29.8	19.8	88°		9.6		29.8	19.8	19.8	25.3	16.8	25.3	16.8	16.8

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THE NATIONAL BUREAU OF STANDARDS

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